The Canfranc Axion Detection Experiment

$$m_a = 330 - 460\,\mu\text{eV}$$
$$(\text{W-band: } 86 - 110\,\text{GHz})$$

CADEx

- The CADEx Proposal
- CADEx Status:
  - Haloscope
  - Optics
  - Detectors
  - Infrastructure
  - Science
- The future of CADEx

Bradley J Kavanagh [he/him]

kavanagh@ifca.unican.es

20th PATRAS Workshop

25 September 2025

IFCA Instituto de Física de Cantabria

50 UC Universidad de Cantabria

CSIC Consejo Superior de Investigaciones Científicas

Gobierno de España Ministerio de Ciencia, Innovación y Universidades

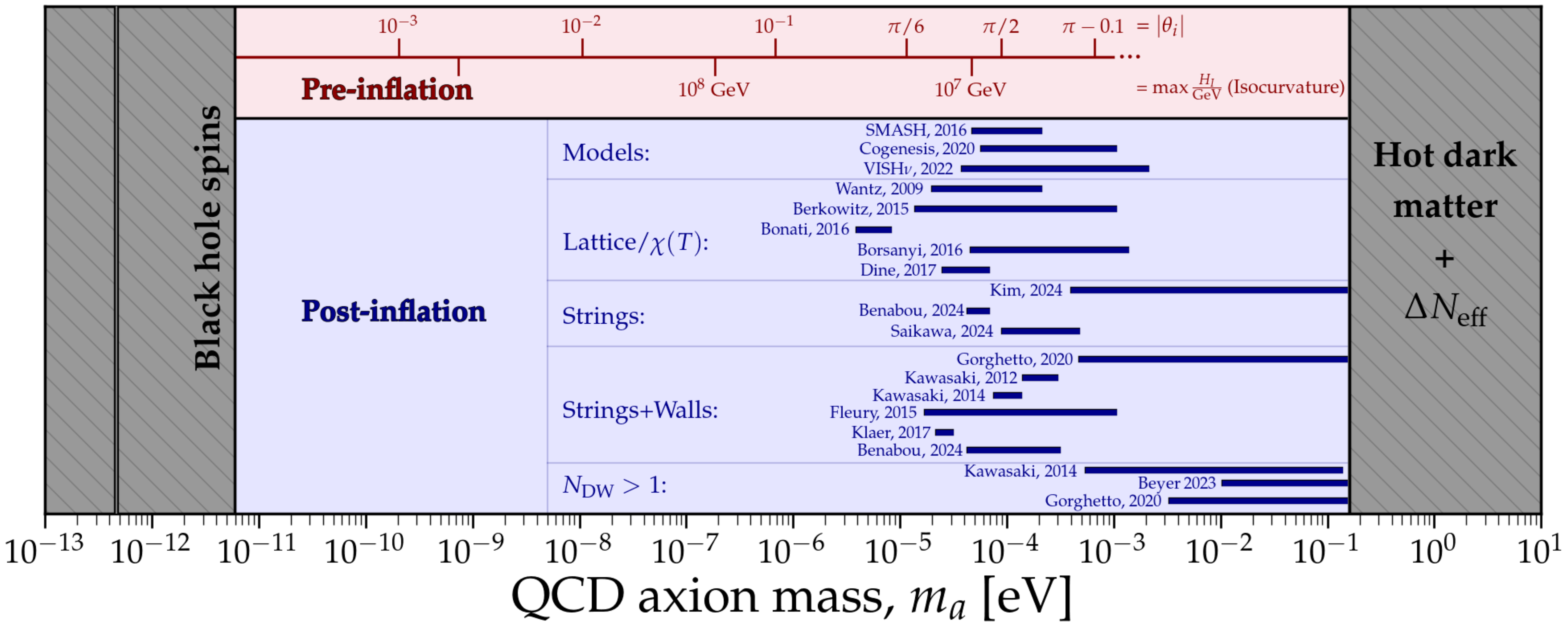
Unión Europea Fondo Europeo de Desarrollo Regional "Una manera de hacer Europa"

Agencia Estatal de Investigación

Dark Matter - Axion Mass

CaDEx

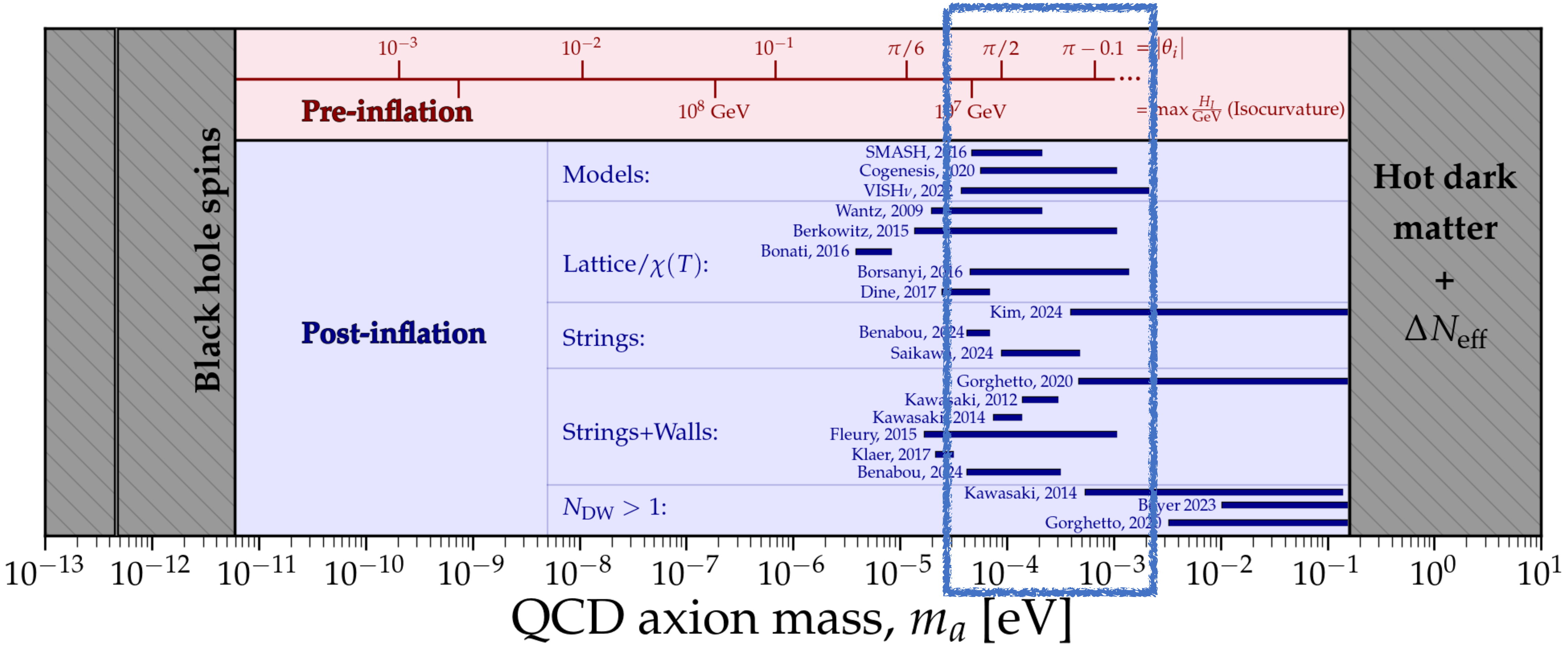
[cajohare.github.io/AxionLimits/]



[See also Javier Redondo's Talk on Tuesday]

Dark Matter - Axion Mass

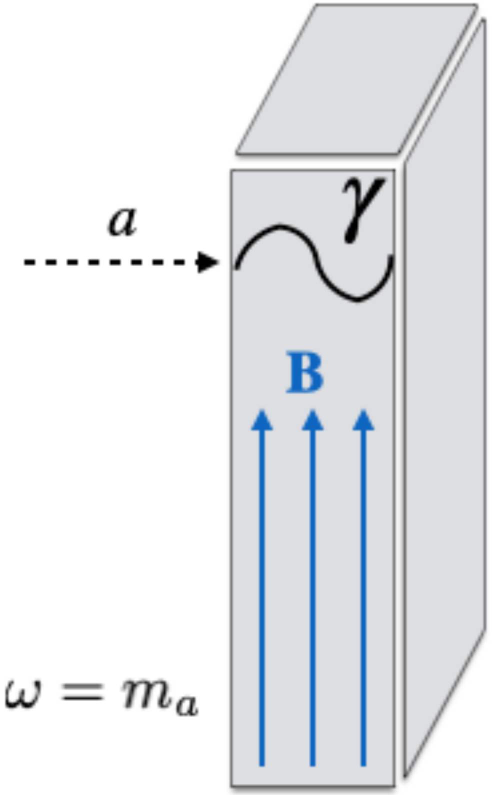
[cajohare.github.io/AxionLimits/]

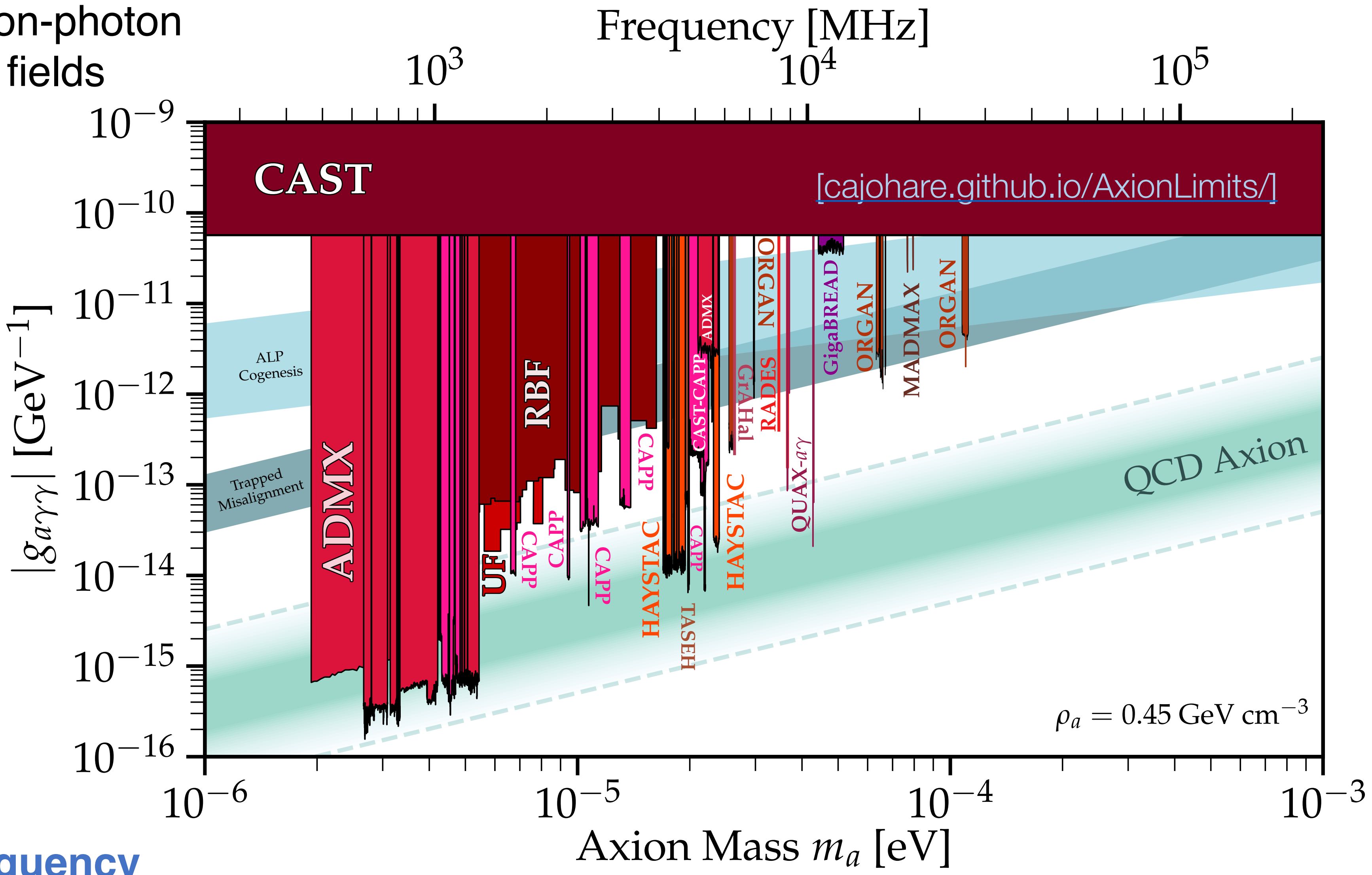


[See also Javier Redondo's Talk on Tuesday]

Haloscope Searches

Inverse Primakoff effect: axion-photon conversion in strong magnetic fields

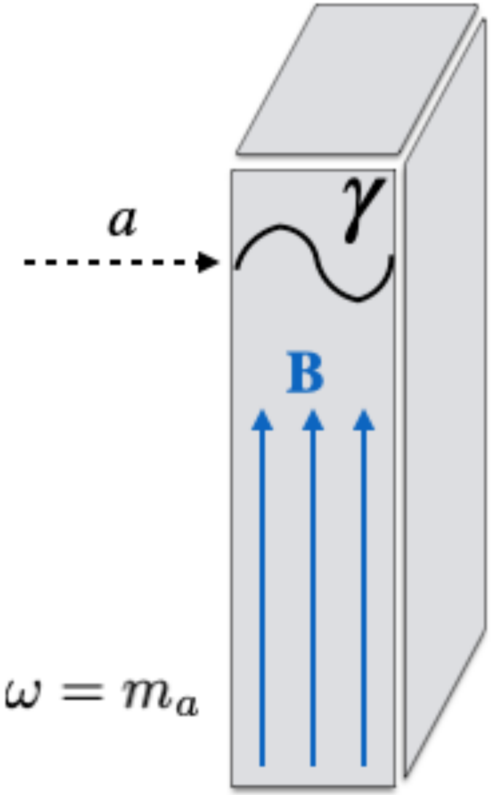


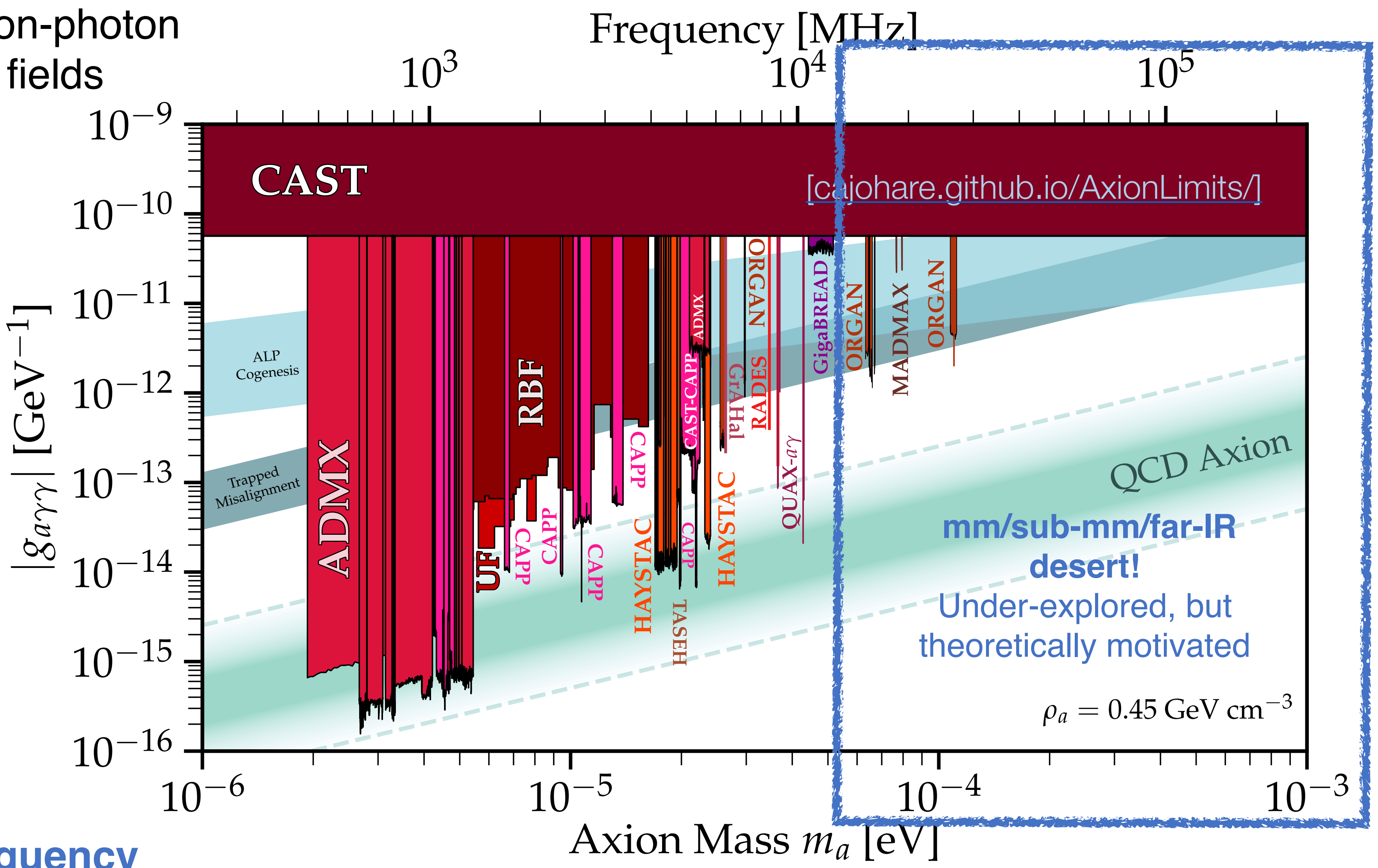


Axion mass ↔ Photon Frequency

Haloscope Searches

Inverse Primakoff effect: axion-photon conversion in strong magnetic fields





Axion mass ↔ Photon Frequency

Canfranc Axion Detection Experiment

CADEx: a novel and challenging experiment to search for dark matter axions in the range m_a = 330–460 μeV (W-band: 86–110 GHz). Also sensitive to dark photons.

Originally proposed and accepted by Canfranc Underground Laboratory (LSC) under EoI-31-2021

Novel Design:

- High frequency, tunable resonant cavities
- Superconducting Kinetic Inductance Detectors (KIDs)
  → broadband, polarisation detectors to go beyond the Standard Quantum Limit
- Eventually need to go underground (at LSC) to shield KIDs from Cosmic Rays

CADEx as a technology platform!

[JCAP 11 (2022) 044, arXiv:2206.02980]

[Cosmic WISPers 2024 Proceedings]

CADEx Team

CADEx

More than 30 people from 11 institutions

CENTRO DE ASTROBIOLOGÍA CSIC - INTA

instituto imdea nanociencia

IFCA

UC UNIVERSIDAD DE CANTABRIA

Observatorio de Yebes
Infraestructura Científica y Técnica Singular

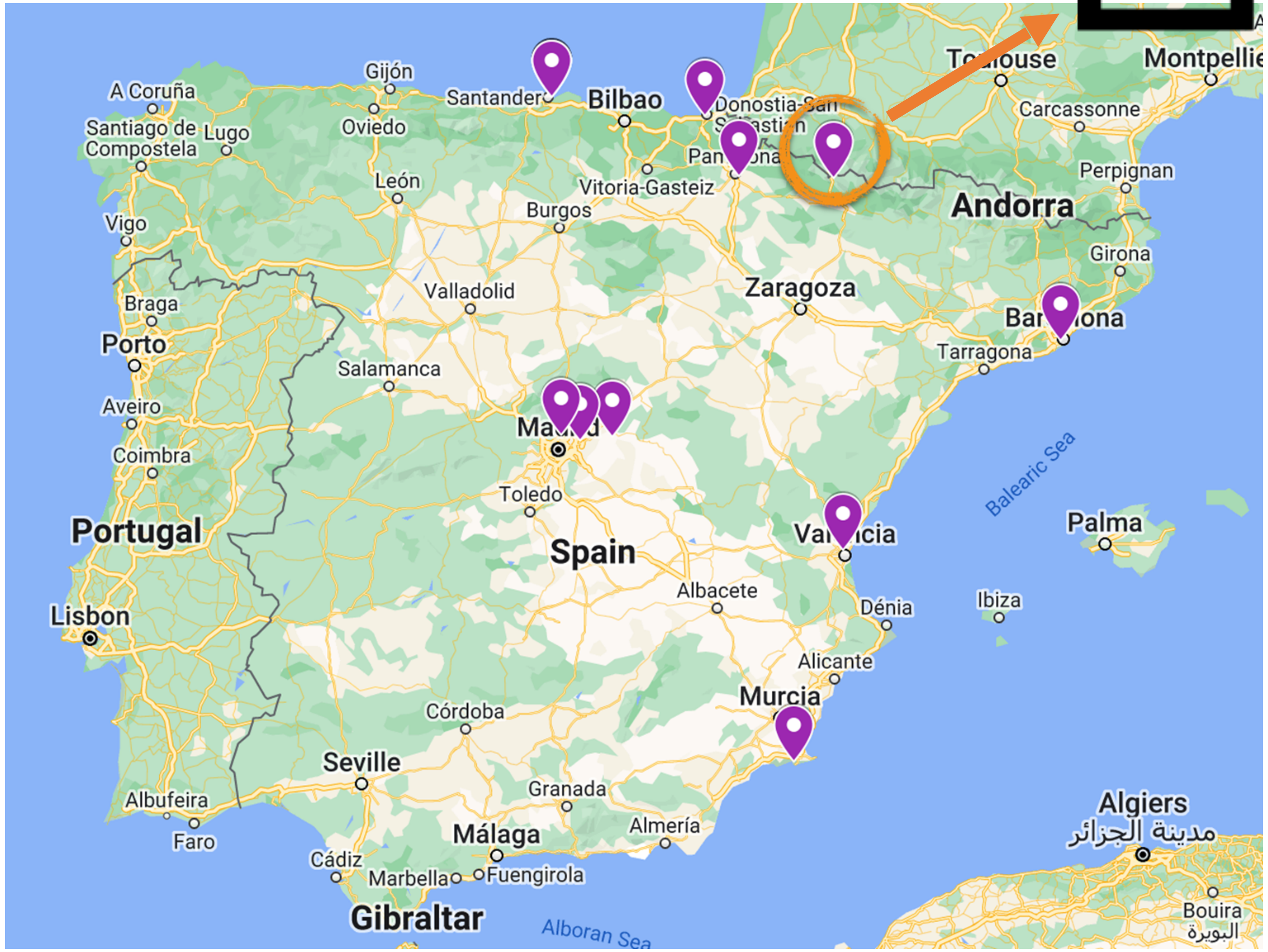
ICCUB

UNIVERSIDAD POLITÉCNICA DE CARTAGENA Fechos Allend Mar

ANTERAL
Innovative Antenna and Terahertz Imaging Technologies

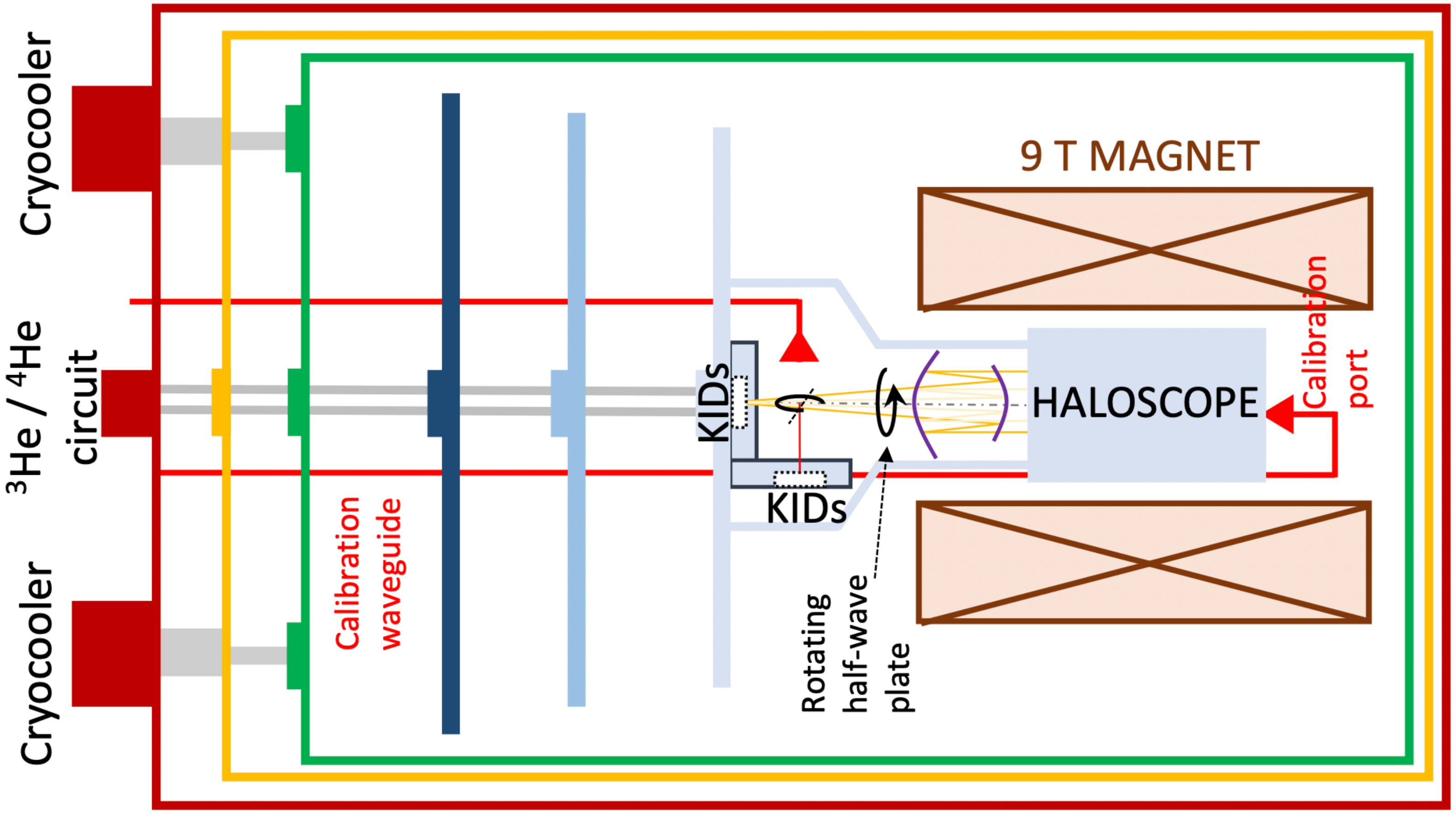
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

upna
Universidad Pública de Navarra
Nafarroako Unibertsitate Publikoa



CADEx Conceptual Design

- Immerse **haloscope array** in high static B = 8-10 T.
- Aim to discriminate the **polarized axion-photon conversion signal** from the unpolarized background.
- Detection system based on **Kinetic Inductance Detectors**.
- Cryogenic background at **T = 100 mK**.

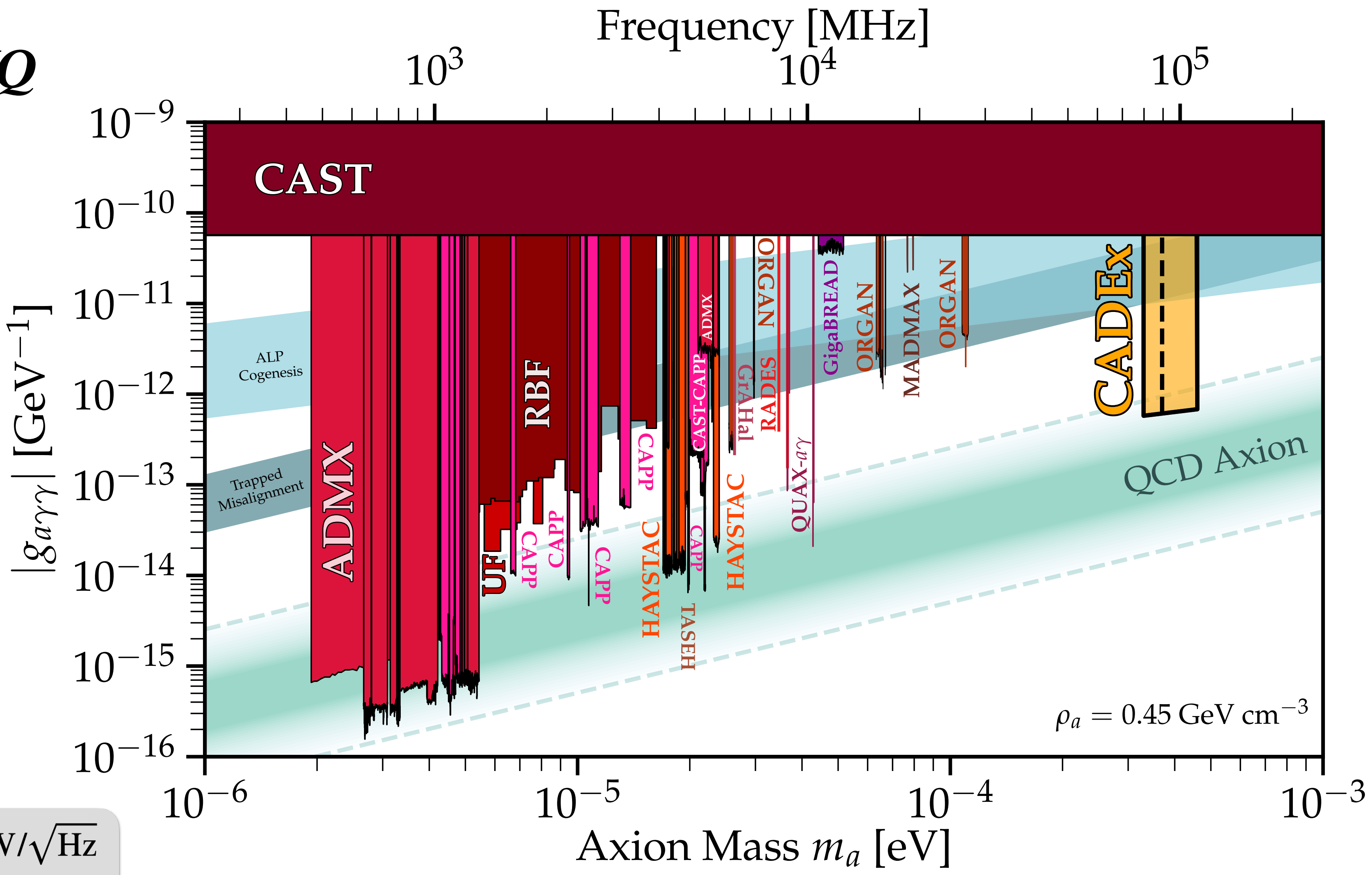


CADEx Sensitivity Projections

$$P_d = \frac{\beta}{(1+\beta)^2} g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 C V Q$$

Magnetic field: $B = 8\text{T}$
Total cavity volume: $V = 0.2\text{L}$
Cavity quality factor: $Q_0 = 2 \times 10^4$

Cavity coupling: $\beta \sim 1$
Cavity form factor: $C \sim 0.66$



- - - - 3 month exposure with NEP = $10^{-19}\ \text{W}/\sqrt{\text{Hz}}$

—— 8 year scan with NEP = $3 \times 10^{-20}\ \text{W}/\sqrt{\text{Hz}}$

CADEx Status: Haloscope

[Cartagena, IFIC, Yebes]

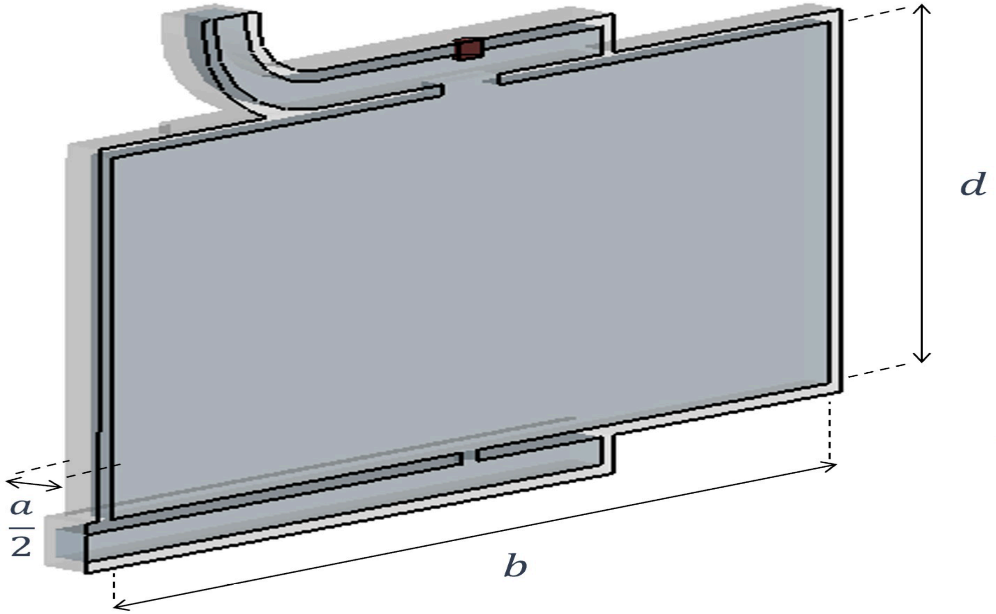
- Pushing 3D Cavities to the **W-band**, two cavities have so far been fabricated

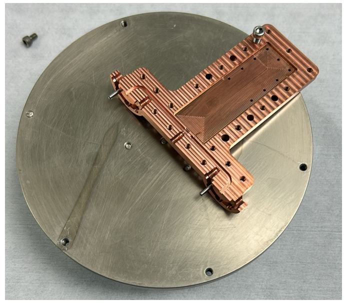
$$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{b^2}}$$

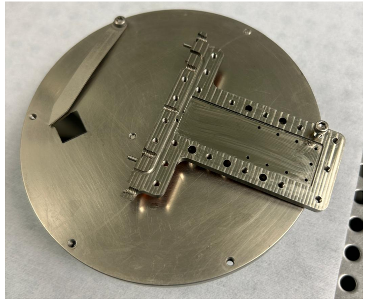
$a \approx 1.7$ mm

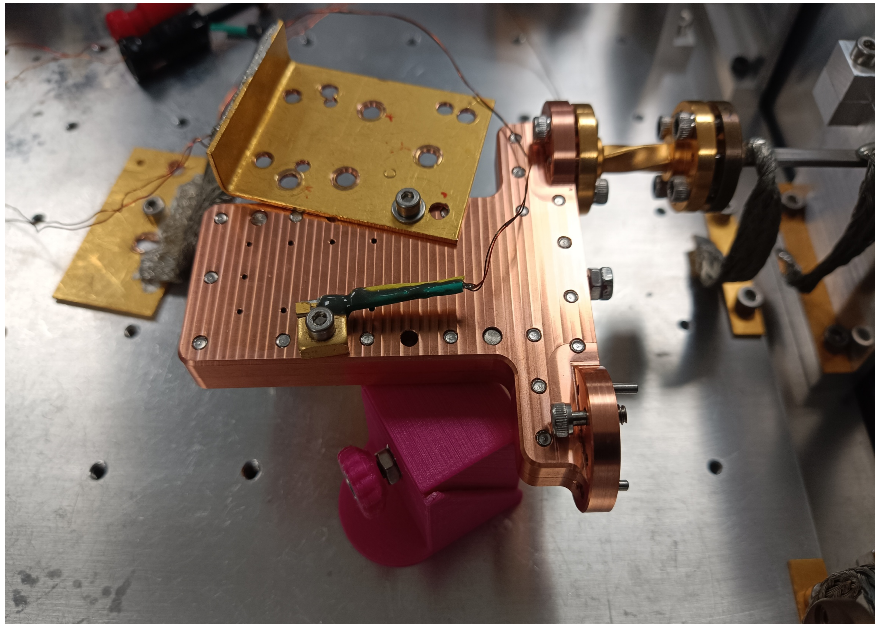
$b = 40a$

$f_r = 90$GHz









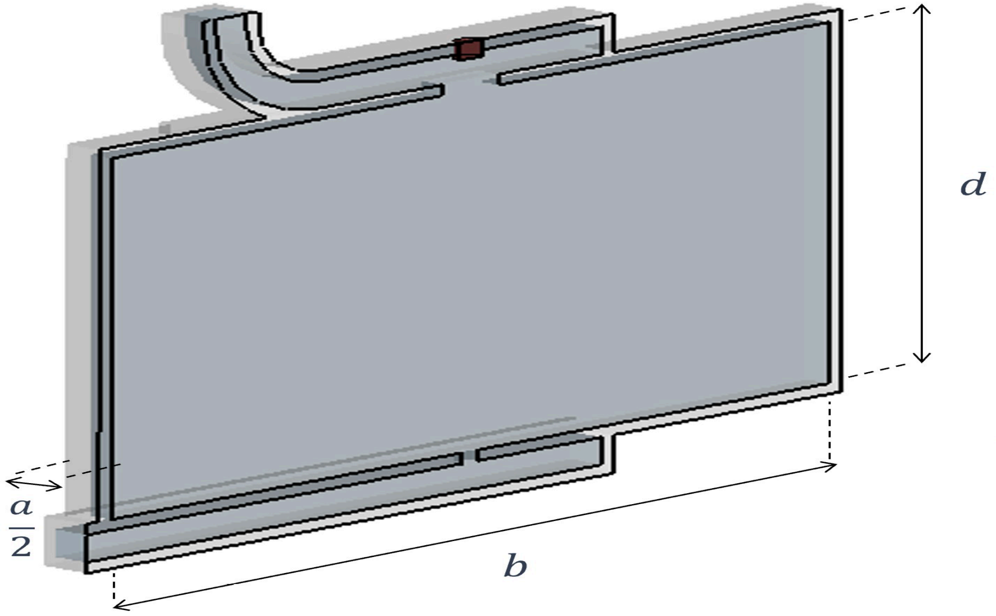
CADEx Status: Haloscope

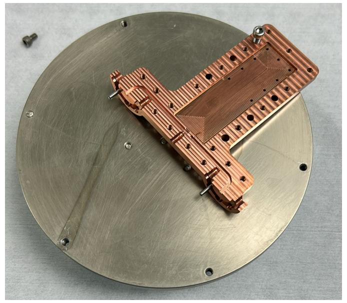
[Cartagena, IFIC, Yebes]

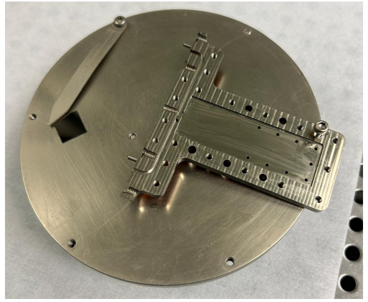
- Pushing 3D Cavities to the **W-band**, two cavities have so far been fabricated

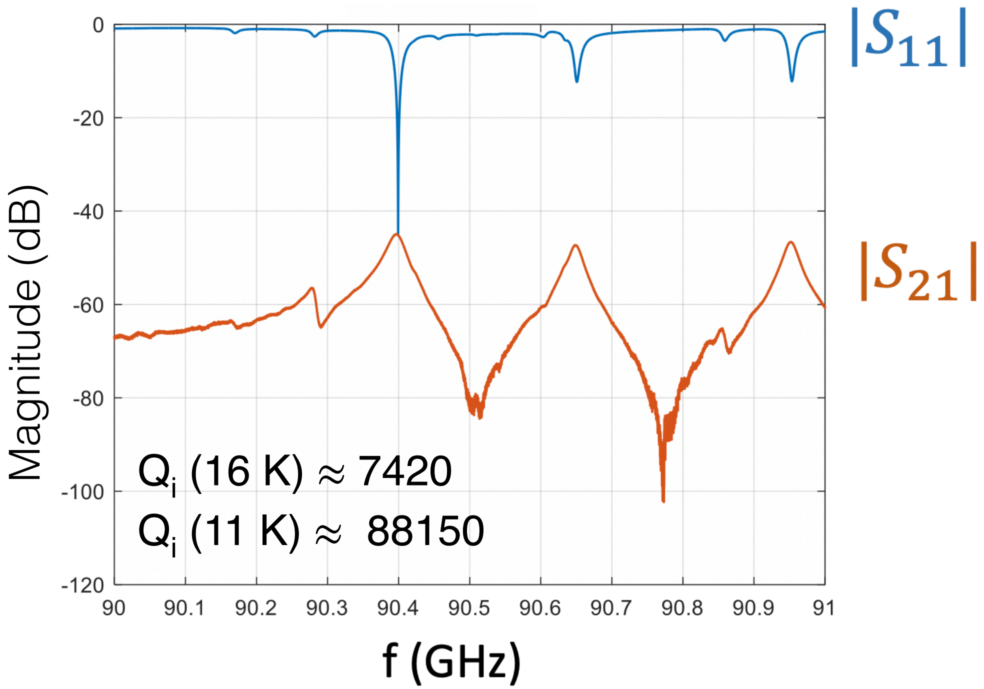
$$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{b^2}}$$

$a \approx 1.7$ mm
$b = 40a$
$f_r = 90$GHz





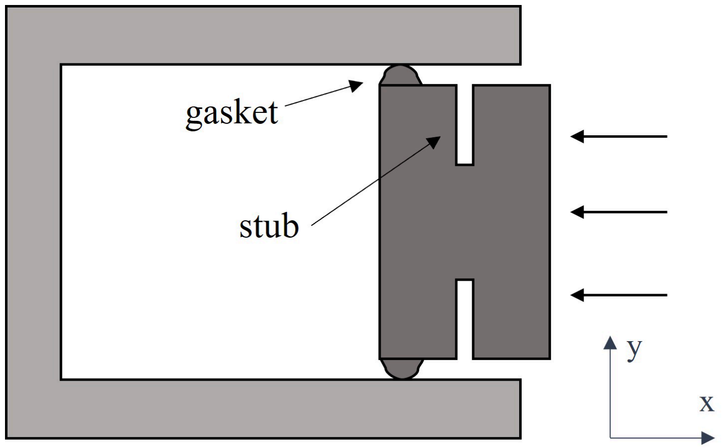


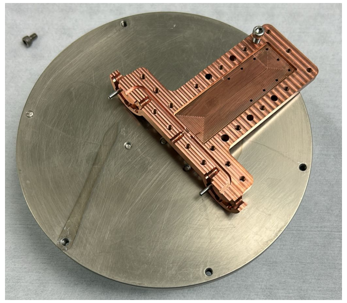


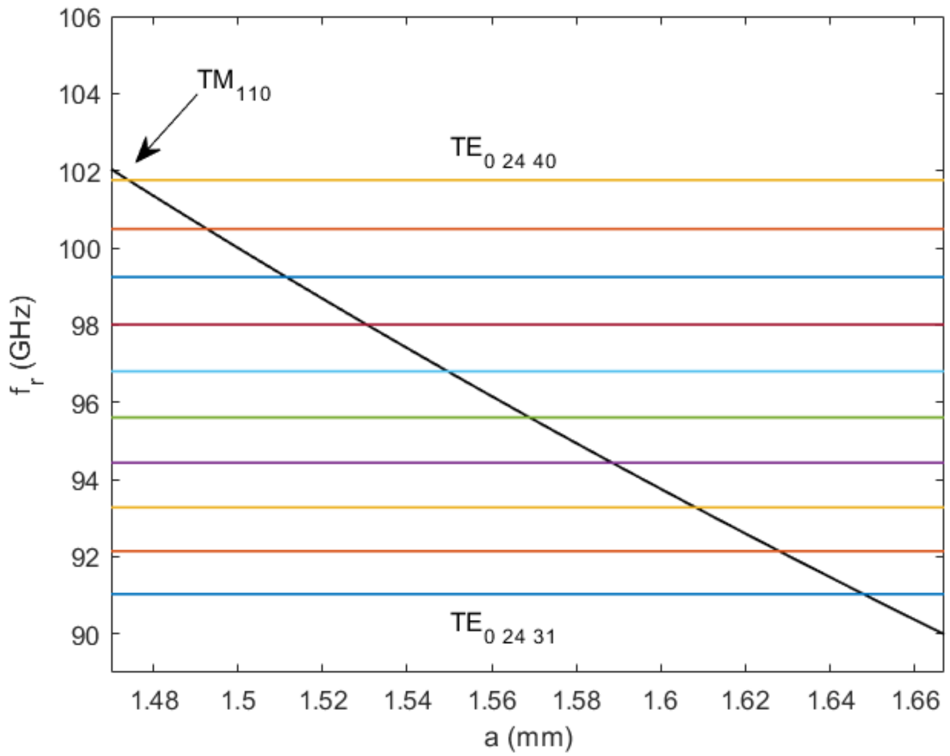
CADEx Status: Haloscope

[Cartagena, IFIC, Yebes]

- Pushing 3D Cavities to the **W-band**, two cavities have so far been fabricated
- Next generation of cavities are **currently being machined**, before being coated with **superconducting NbTiN film** to enhance Q.
- Quality factor measurements in the coming months (Q4 2025)
- Ultimately aim to develop **tunable cavities** to scan frequency range $f_r \in [86, 111]$ GHz





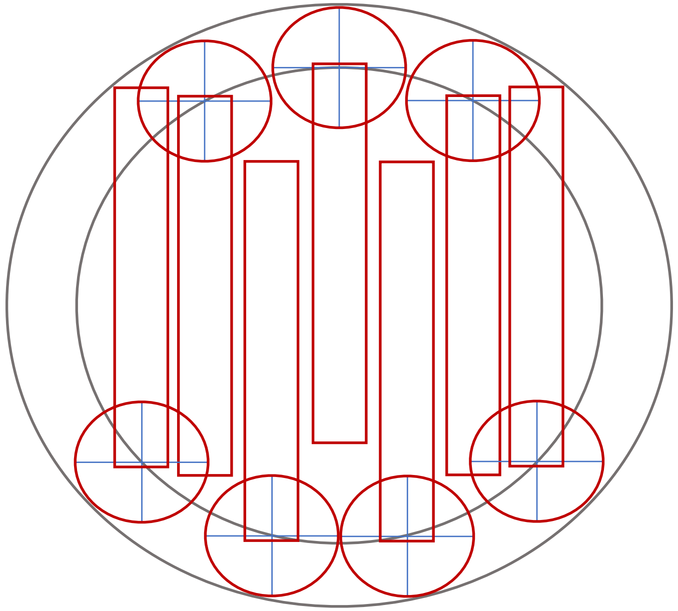


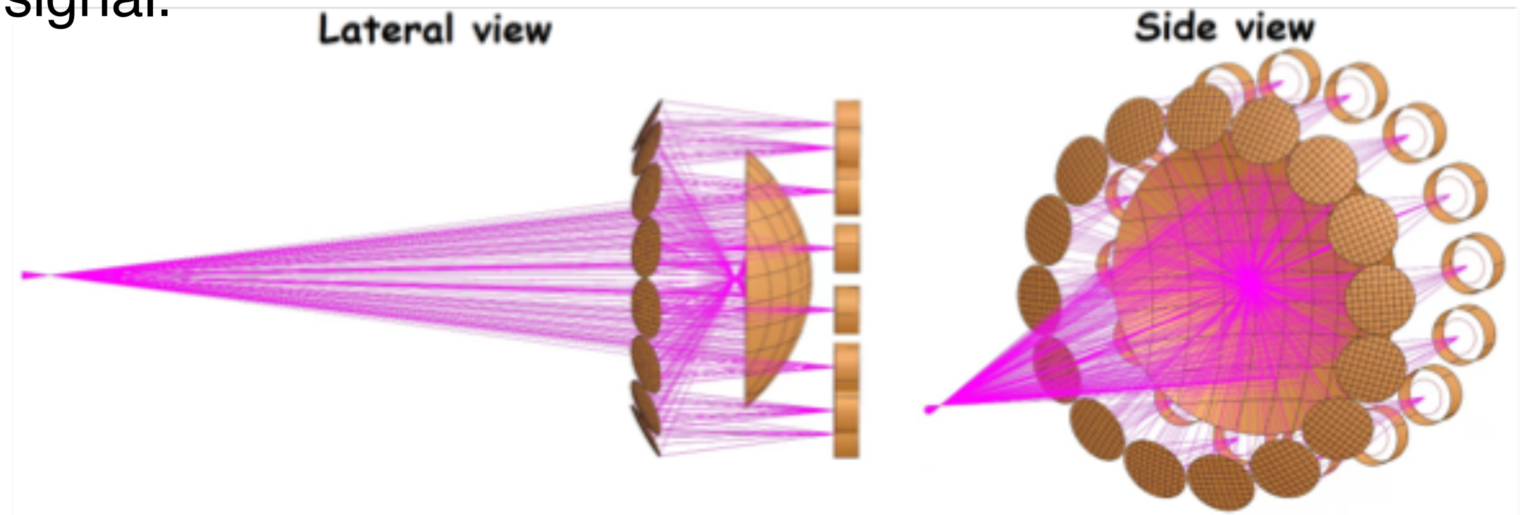
[See e.g. McAllister et al., 2309.12098]

CADEx Status: Optics

[Navarra]

- Need to **maximize volume** → haloscope array!
- **Quasi-optical system** based on 7 horn antennas apertures focus signal going out from the haloscopes to the detection system.
- Polarization needs to be preserved.
- To be fitted in the 100 mK space within the cryogenic system.
- Filters are mandatory to diminish out-of-band background signal.





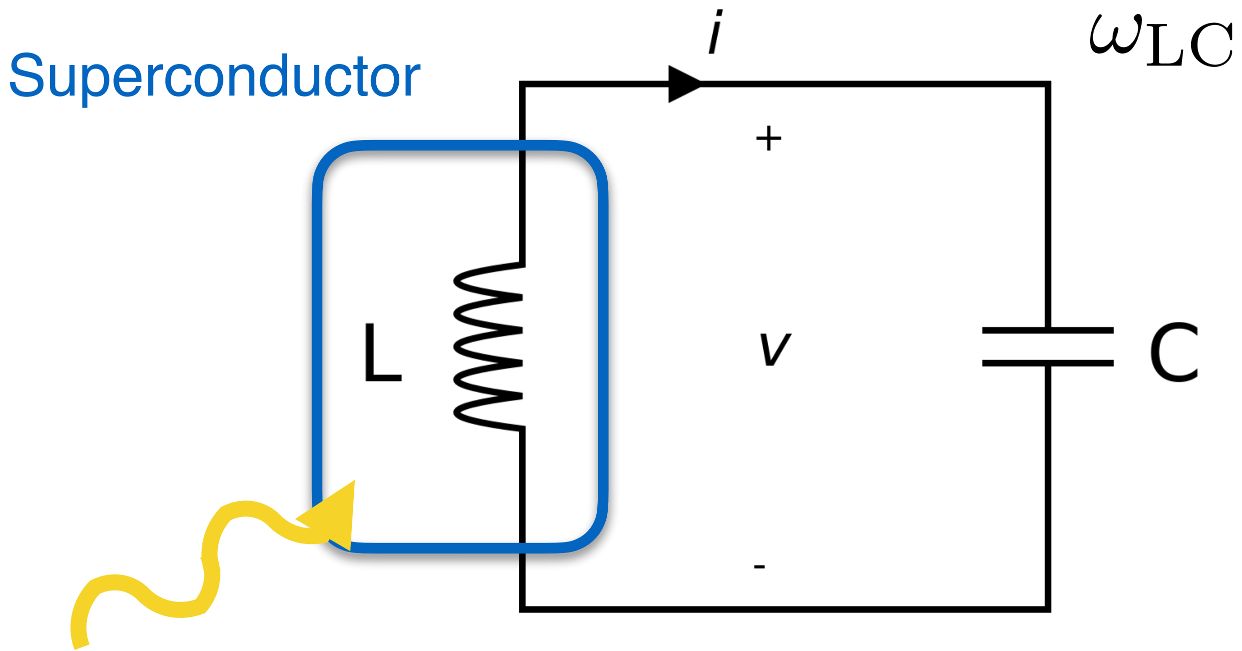
$$P_d = \frac{\beta}{(1+\beta)^2} g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 C \mathbf{VQ}$$

Old design with 16 cavities
(New design is for **7 cavities**)

CADEx Status: KIDs

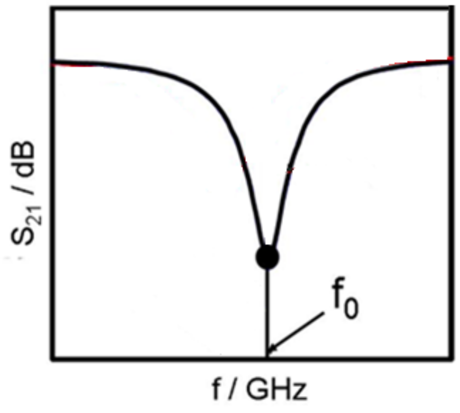
[CAB, University of Cantabria, Yebes, IMDEA]

Kinetic Inductance Detectors (KIDs)



$$f_0 = \frac{1}{\sqrt{LC}}$$

$$f' = \frac{1}{\sqrt{L'C}}$$



Photon absorbed by superconductor breaks Cooper pairs, reducing kinetic inductance

Detection by monitoring the resonant frequency of the LC circuit

Sensitivity described by Noise-equivalent power (NEP):

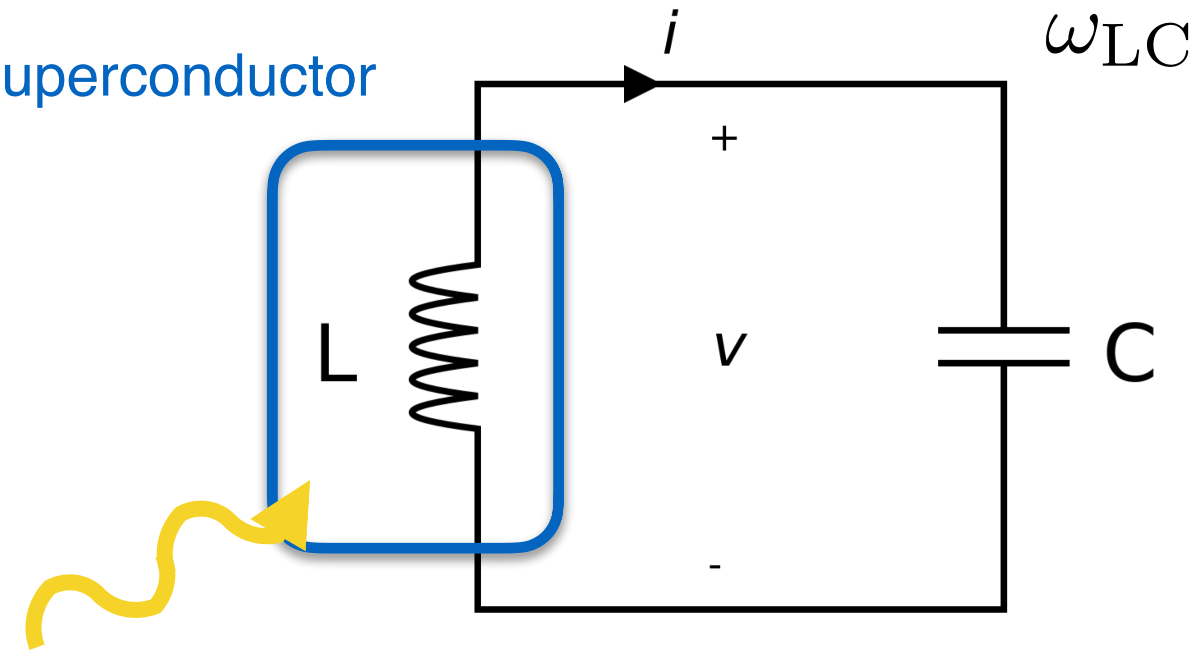
$$\delta P_{\rm noise}^{\rm inc} = \frac{\rm NEP}{\sqrt{2\Delta t}}$$

CADEx Status: KIDs

[CAB, University of Cantabria, Yebes, IMDEA]

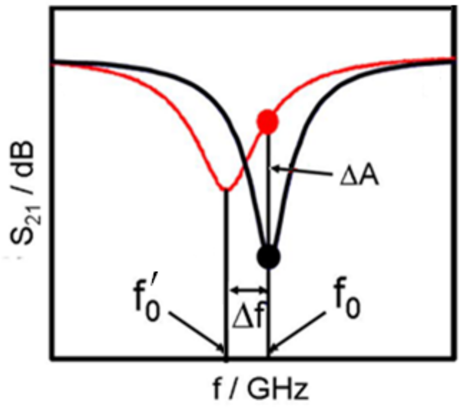
Kinetic Inductance Detectors (KIDs)

Superconductor



$$f_0 = \frac{1}{\sqrt{LC}}$$

$$f' = \frac{1}{\sqrt{L'C}}$$



Photon absorbed by superconductor breaks Cooper pairs, reducing kinetic inductance

Sensitivity described by Noise-equivalent power (NEP):

$$\delta P^{\mathrm{inc}}_{\mathrm{noise}} = \frac{\mathrm{NEP}}{\sqrt{2\Delta t}}$$

Detection by monitoring the resonant frequency of the LC circuit

KIDs Array

[CAB, University of Cantabria, Yebes, IMDEA]

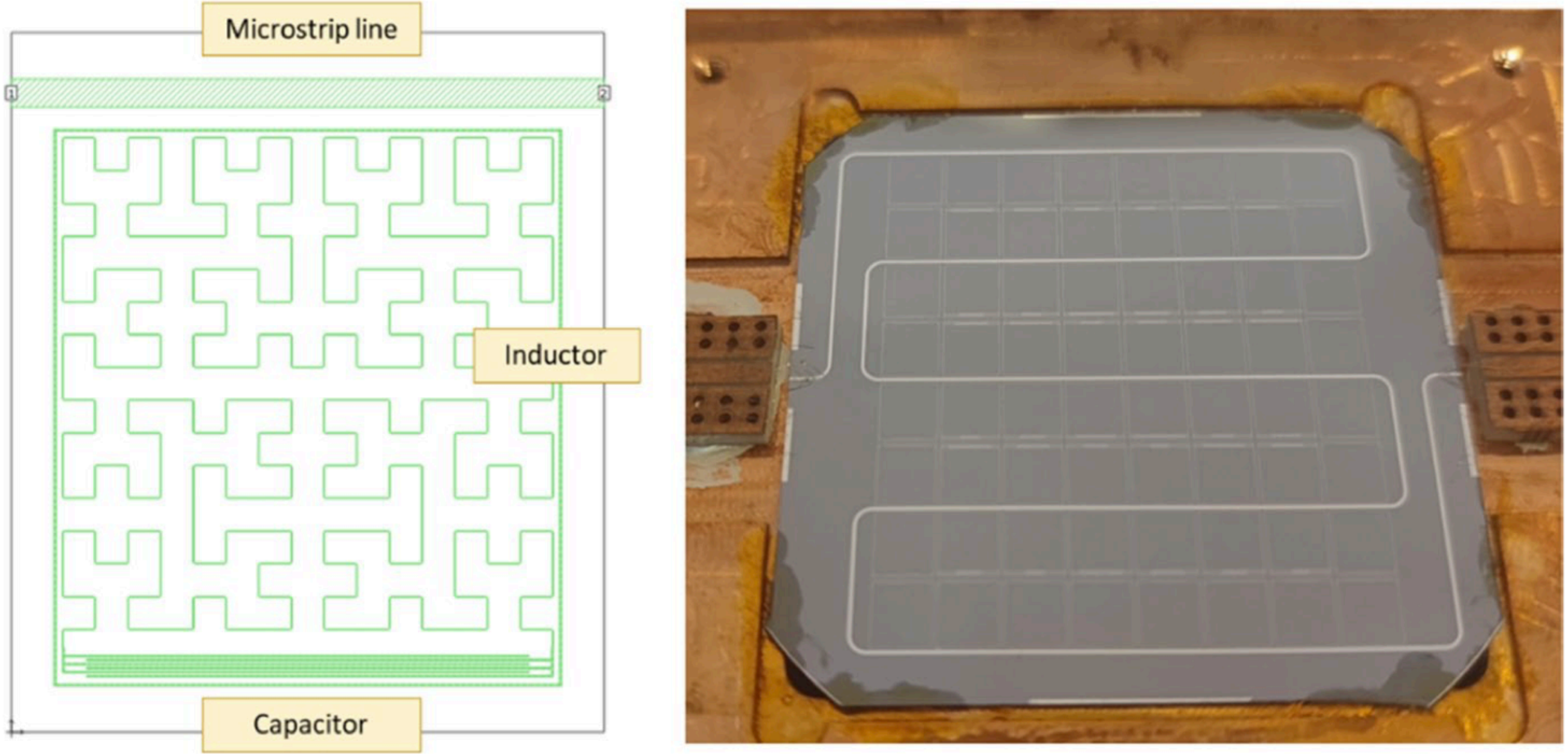


Fig. 1 *Left* schematic of a LEKID coupled to a microstrip read-out line, with the inductor and the inter-digital capacitor. *Right* photograph of the 64 LEKIDs prototype fabricated on a silicon substrate of size 40×40 mm^2

[Journal of Low Temperature Physics (2024)]

KIDs Array

[CAB, University of Cantabria, Yebes, IMDEA]

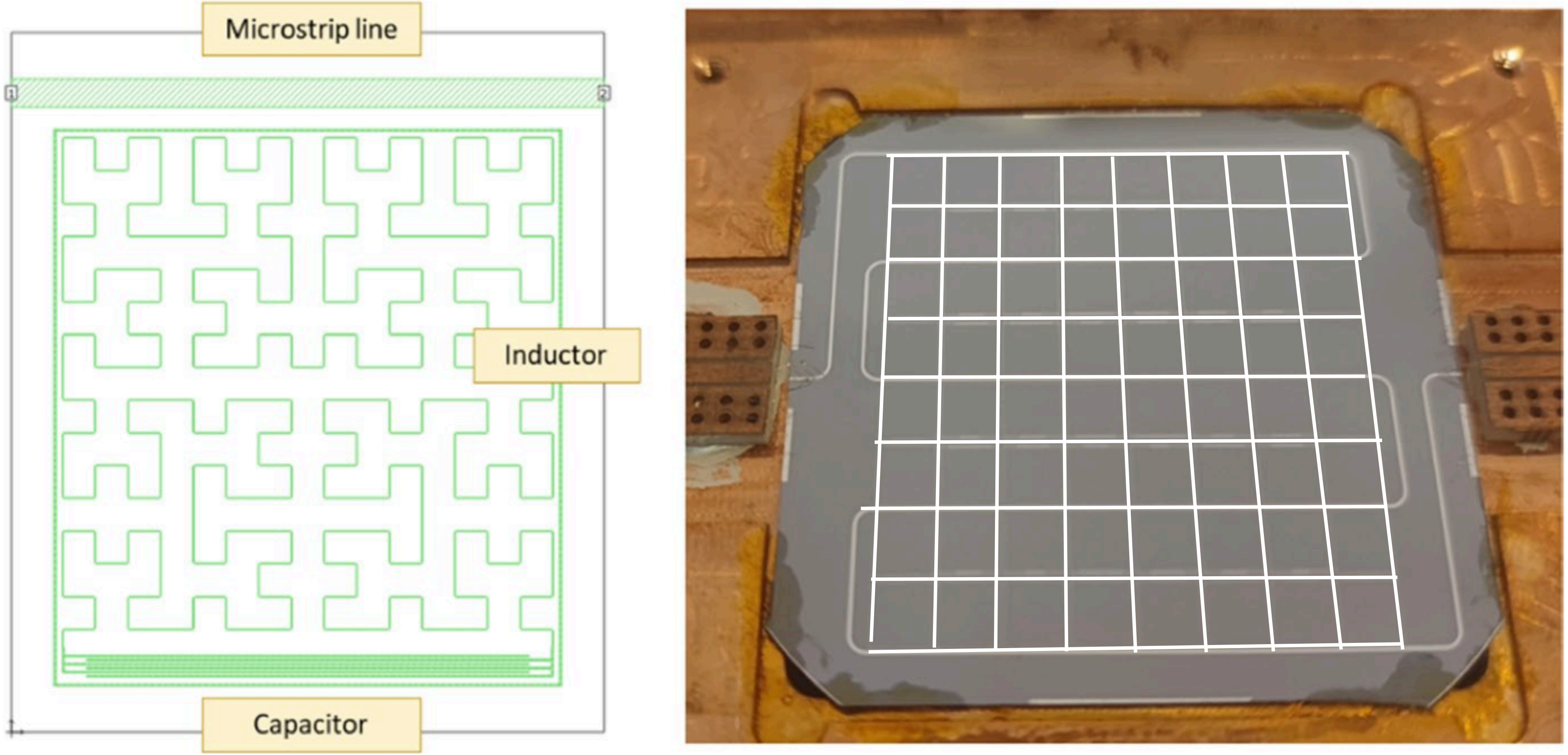


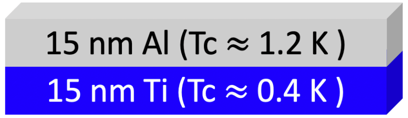
Fig. 1 *Left* schematic of a LEKID coupled to a microstrip read-out line, with the inductor and the interdigital capacitor. *Right* photograph of the 64 LEKIDs prototype fabricated on a silicon substrate of size 40×40 mm^2

[Journal of Low Temperature Physics (2024)]

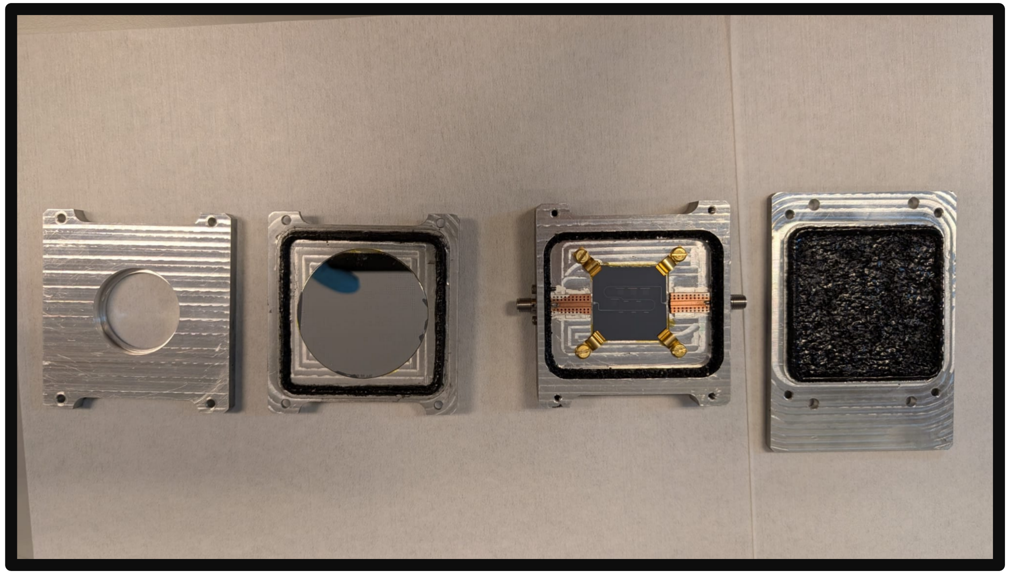
CADEx Status: KIDs

[CAB, University of Cantabria, Yebes, IMDEA]

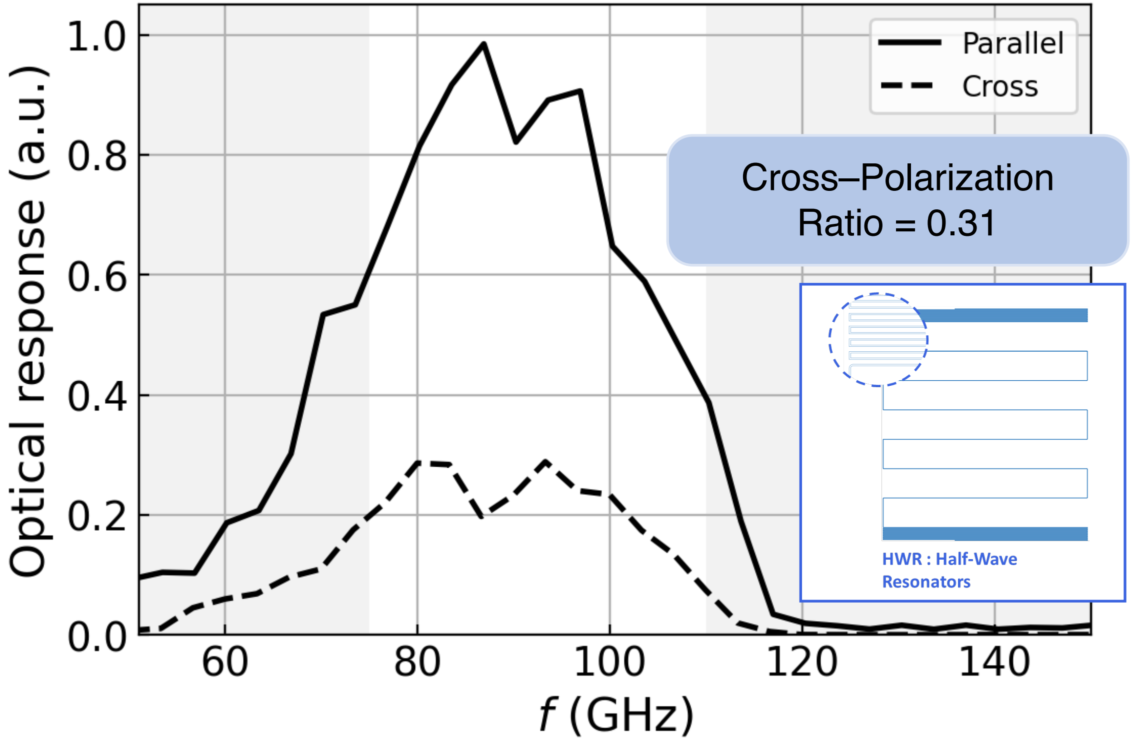
- **Broadband** detection system based on superconducting **Kinetic Inductance Detectors**
- First demonstrators based on **Ti/Al bilayer** have been developed and characterized
- Cryogenic response confirms **W-band detection**.
- KIDs demonstrated **background limited performance** (T_{bb} = 50 K).
- **Low background set-up** under test



[See also Journal of Low Temperature Physics (2024)]



Target NEP $\leq 10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$

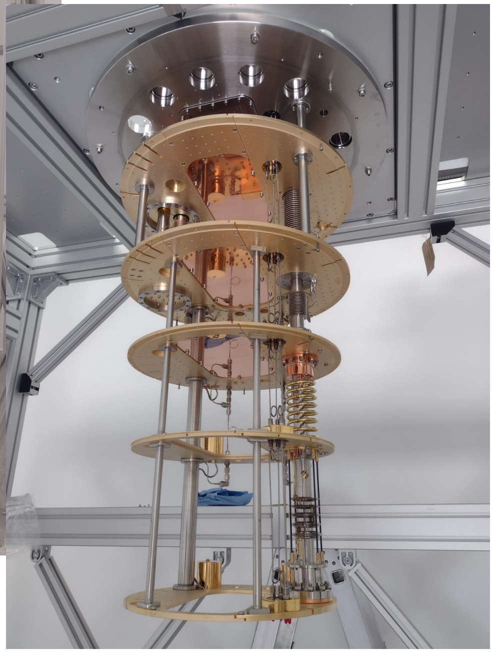


CADEx Status: Infrastructure

[IFCA]

CADEx

- **IFCA Cryolab:** New cryogenic laboratory at IFCA will host CADEx technology demonstrator - civil work recently completed in Summer 2025*
- Installation of dilution refrigerator now completed
- Cryolab will be a **test bed of quantum sensor technologies**. Pathfinder setup will be used to test, compare and optimise detectors
- Currently tendering for the magnet.



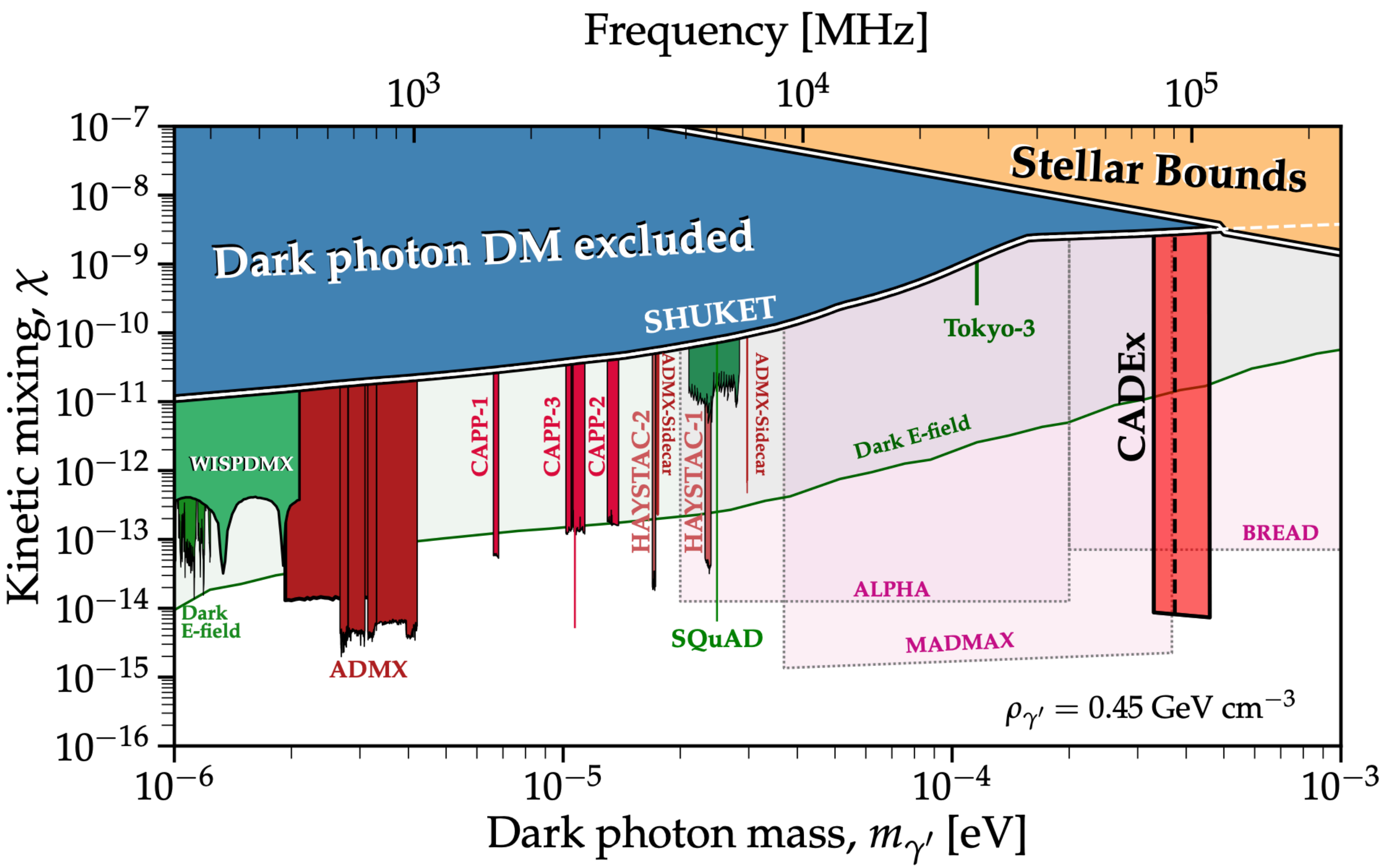
*IFCA cryolab also to be used for e.g. development of the thermal monitoring and control system (TMCS) system for the LiteBird experiment (CMB polarisation satellite, Cosmology Group)

QTEP

CADEx Status: Science

[IFCA & ICCUB]

- Updating sensitivity estimates, as design is updated and finalised
- Developing the **data analysis strategy** - broadband detection means spectral information of signal cannot be used to discriminate from background!
- Expanding the proposed search beyond axion (Dark Photons? Scalars? Gravitational Waves?)



CADEx Timeline

Existing EoI with LSC runs throughs through 2026. What does the future look like?

- **Design and Demonstration Phase (2 years)**

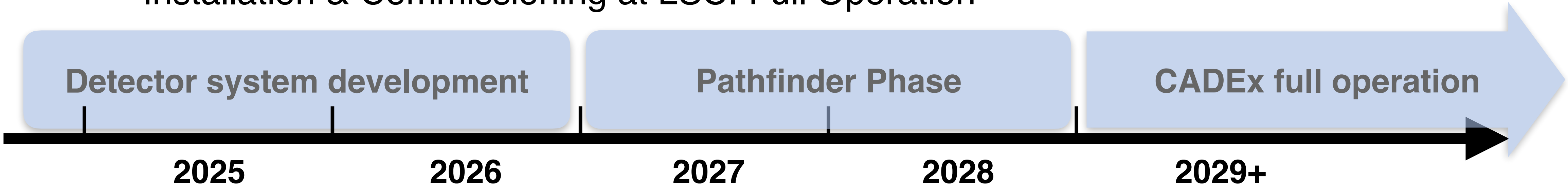
  Cryostat acquisition, installation and operation
  Full quasi-optical design
  Demonstration of key technology (haloscope and detectors) in the lab.

- **Pathfinder Phase (2 years)**

  First CADEx prototype (pathfinder) to be installed & tested in IFCA Cryolab
  First science results in 2027/2028

- **Operation Phase (8 years)**

  Upgrade the experiment to improve the sensitivity
  Installation & Commissioning at LSC. Full Operation

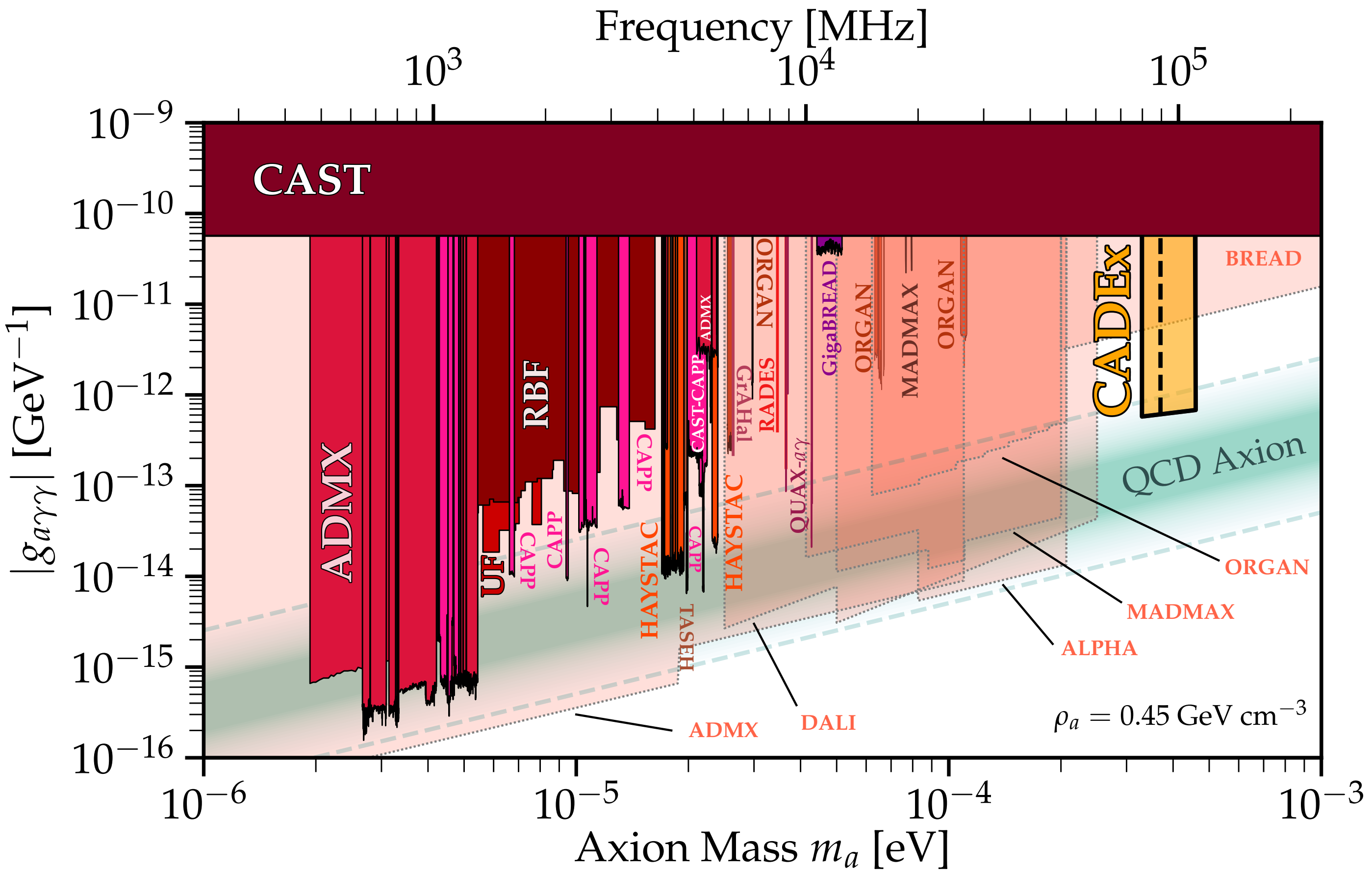


Summary

- **CADEx:** a novel search for Dark Matter axions (and more?) in a well-motivated but under-explored part of parameter space

- Substantial **technological challenge** (but also a platform for development and testing of new sensors)

- **Complementary** to proposed non-haloscope high-frequency axion searches

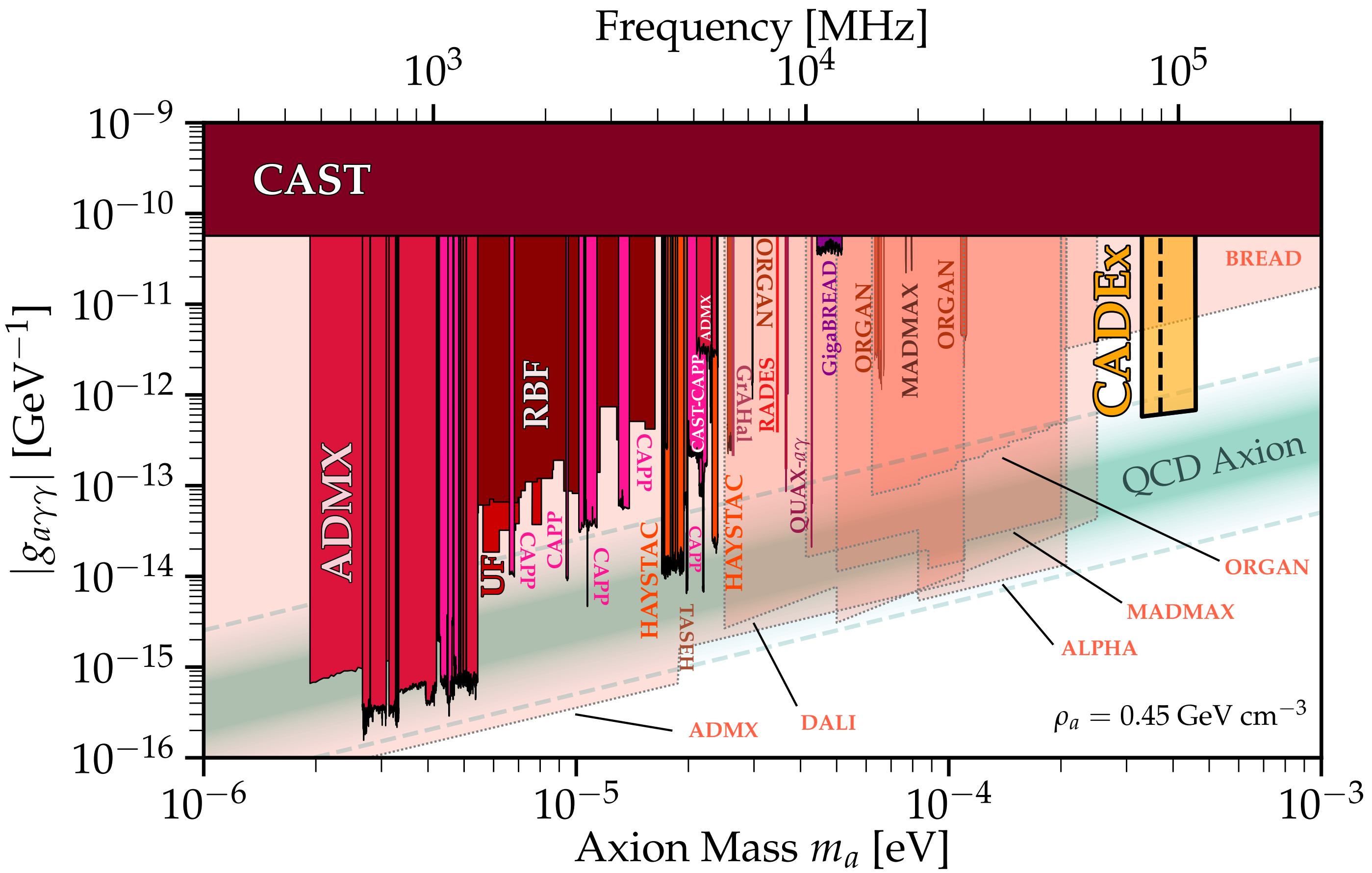


- Development of haloscopes, optics and detectors are underway, with **installation of the pathfinder *planned* for 2026** → first science results expected in 2027/2028

Summary

Thank you!

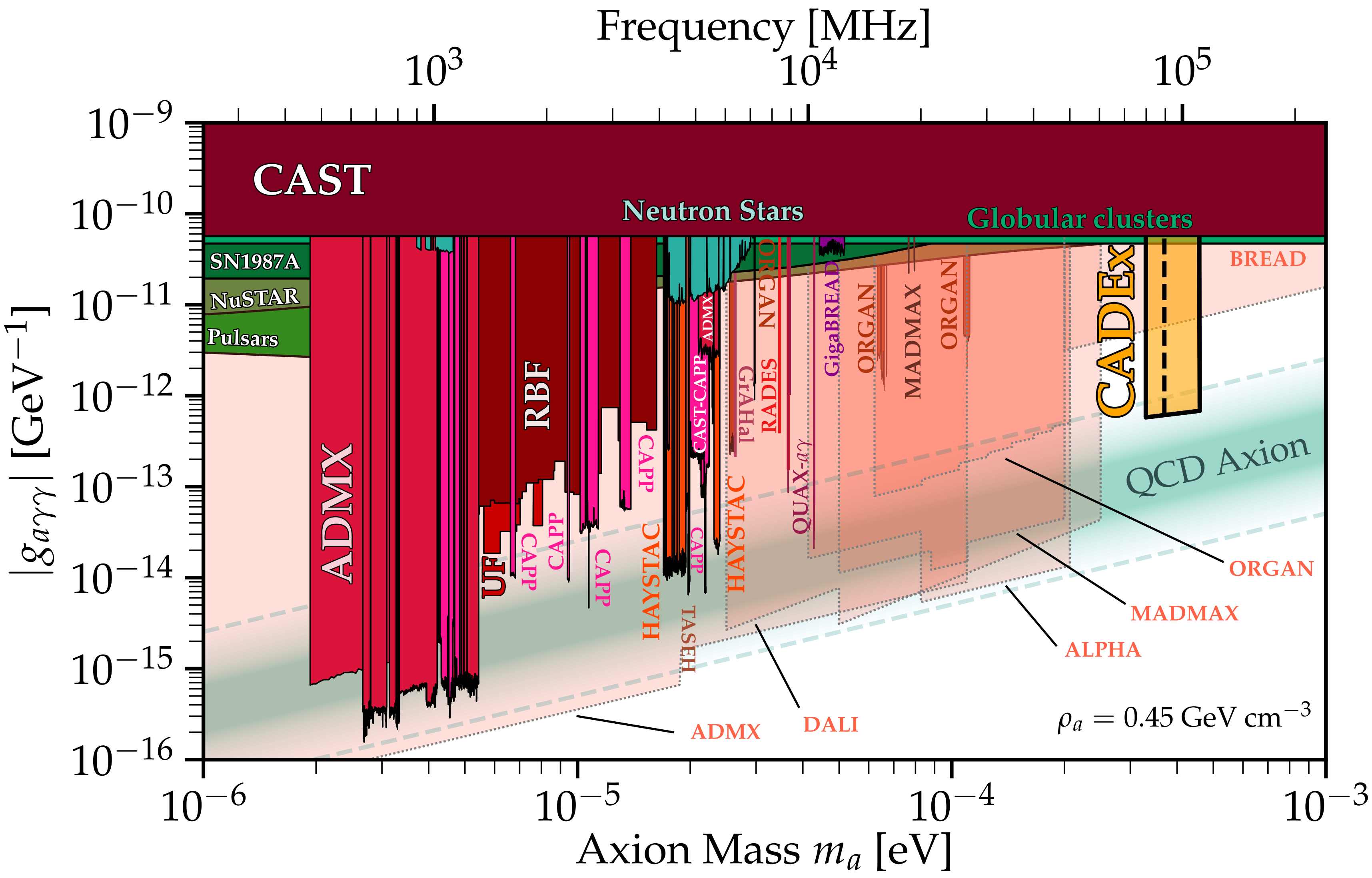
- **CADEx:** a novel search for Dark Matter axions (and more?) in a well-motivated but under-explored part of parameter space
- Substantial **technological challenge** (but also a platform for development and testing of new sensors)
- **Complementary** to proposed non-haloscope high-frequency axion searches



- Development of haloscopes, optics and detectors are underway, with **installation of the pathfinder *planned* for 2026** → first science results expected in 2027/2028

Backup slides

Axion Landscape



Detector systems

CADEx

Heterodyne (Coherent)	**KIDs (Incoherent)**
$$\delta P_{\rm noise}^{\rm coh} = k_B T_{\rm sys}\sqrt{\frac{\Delta\nu}{\Delta t}}$$	$$\delta P_{\rm noise}^{\rm inc} = \frac{\rm NEP}{\sqrt{2\Delta t}}$$

Question: what value of $\Delta\nu$ should we be considering here? What is the optimal value?

Signal power and brightness temperature related as:

$$P_s = k_B T_s \Delta\nu_s$$

$$\delta P_{\rm noise} \propto 1/\sqrt{\Delta t}$$

for integration time Δt

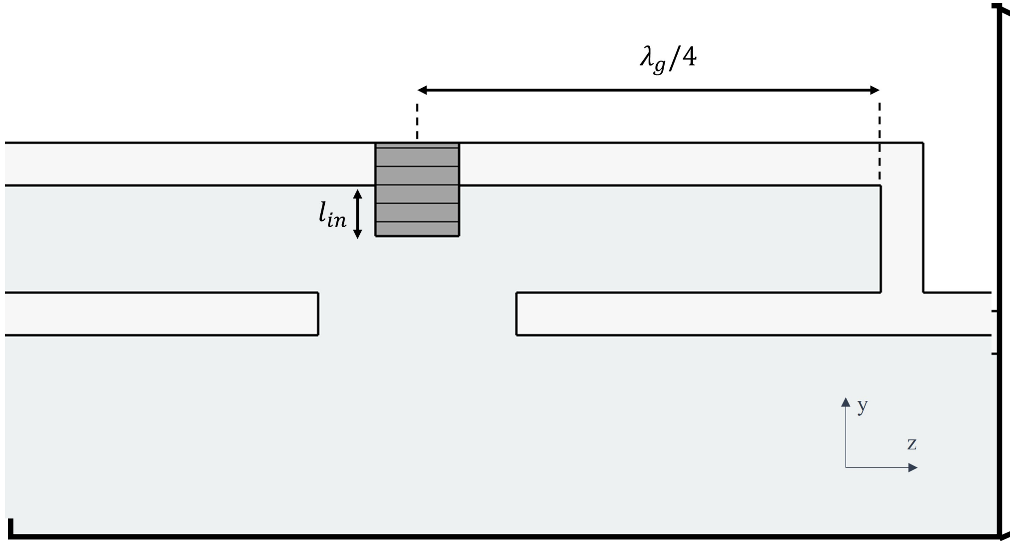
For heterodyne detectors, use correspondence:

$$\mathrm{NEP} \leftrightarrow k_B T_{\rm sys}\sqrt{2\Delta\nu}$$

Haloscope Coupling

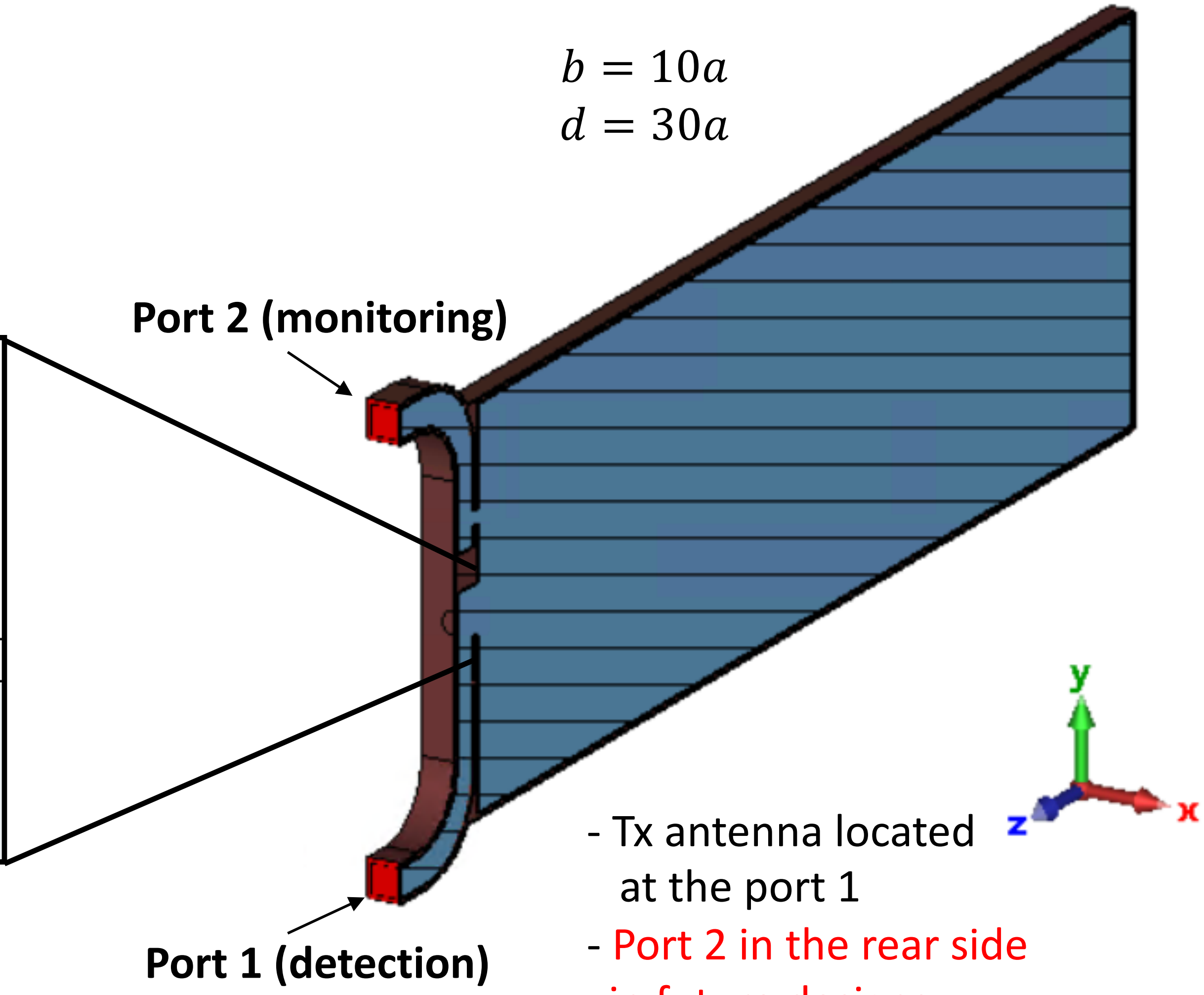
Bended waveguides are needed to orient the signal to the horn antennas

Coupling screw system



Needed to recouple the waveguide to the cavity

$b = 10a$
$d = 30a$

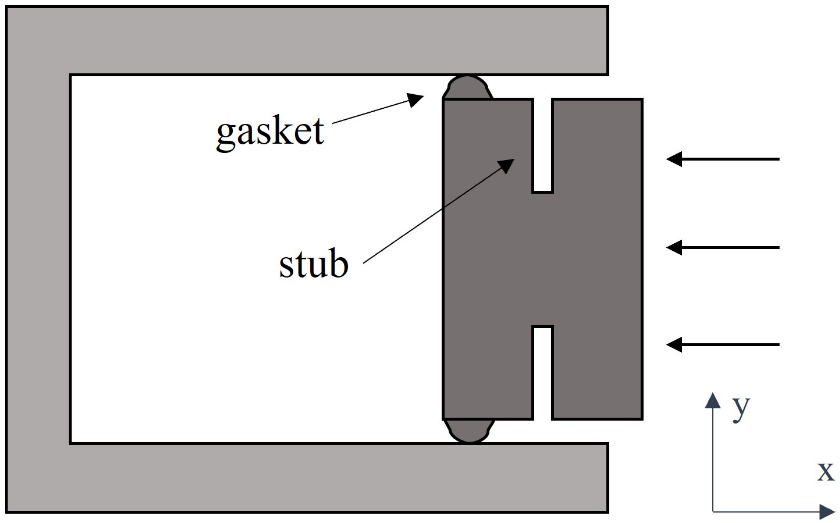


- Tx antenna located at the port 1
- Port 2 in the rear side in future designs

Tunable Cavities

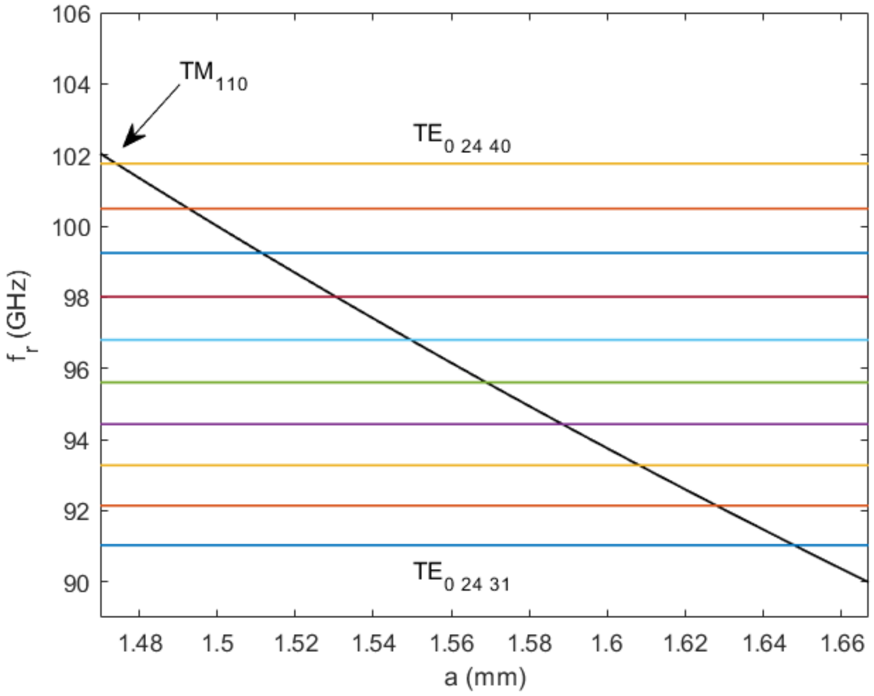
- Tuning is required to scan different masses with a single cavity

Tuning system based on a **sliding wall**

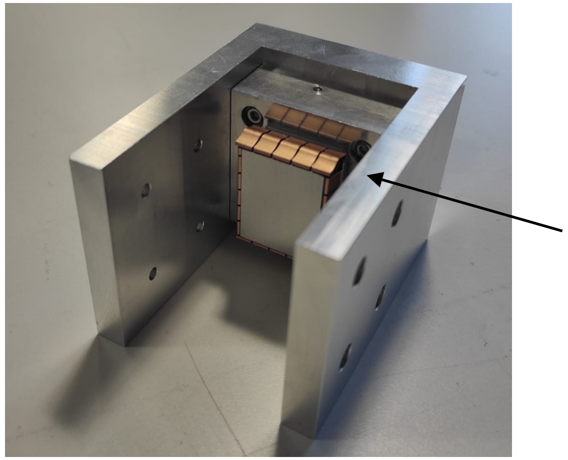


Gaskets and stubs are incorporated to **reduce losses**

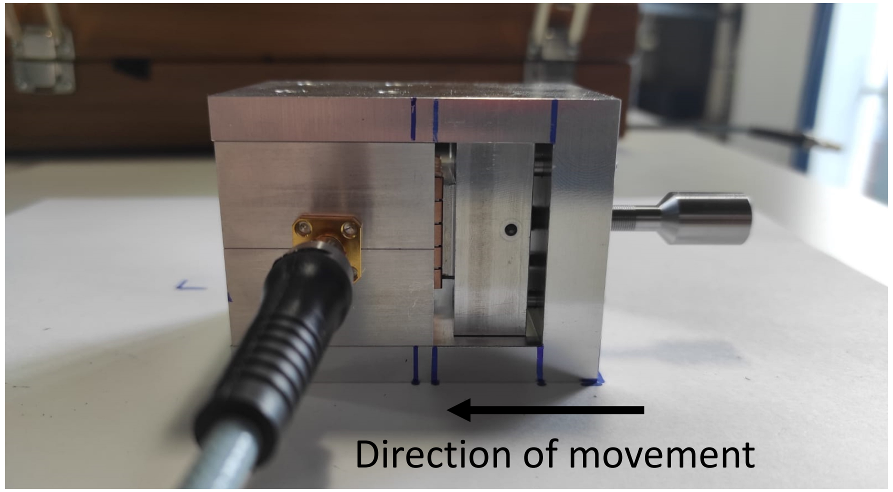
By changing the width the resonant frequency is varied

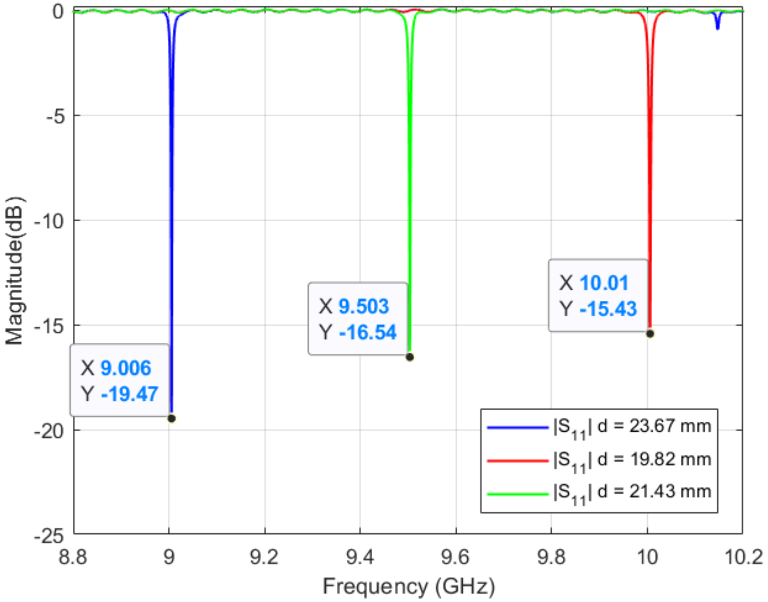


Tunable Cavities



Manufactured sliding wall + gaskets prototype in X-Band (9-10 GHz)





Compared with theoretical Q_0

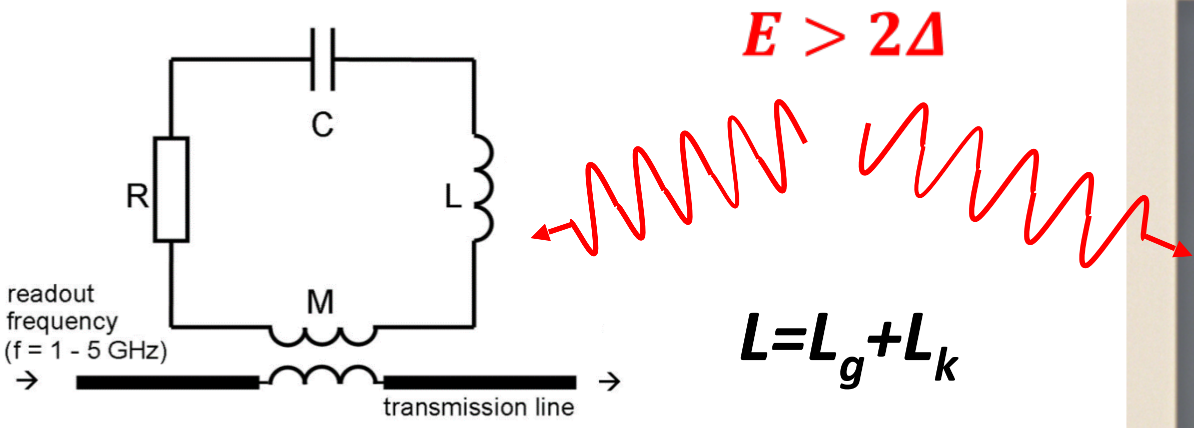
Gaskets maintain **56%** of the theoretical Q_0

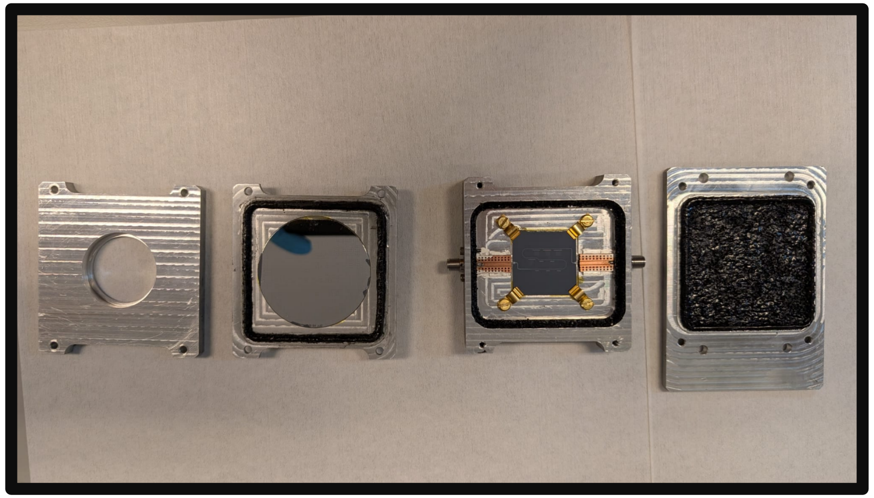
↓

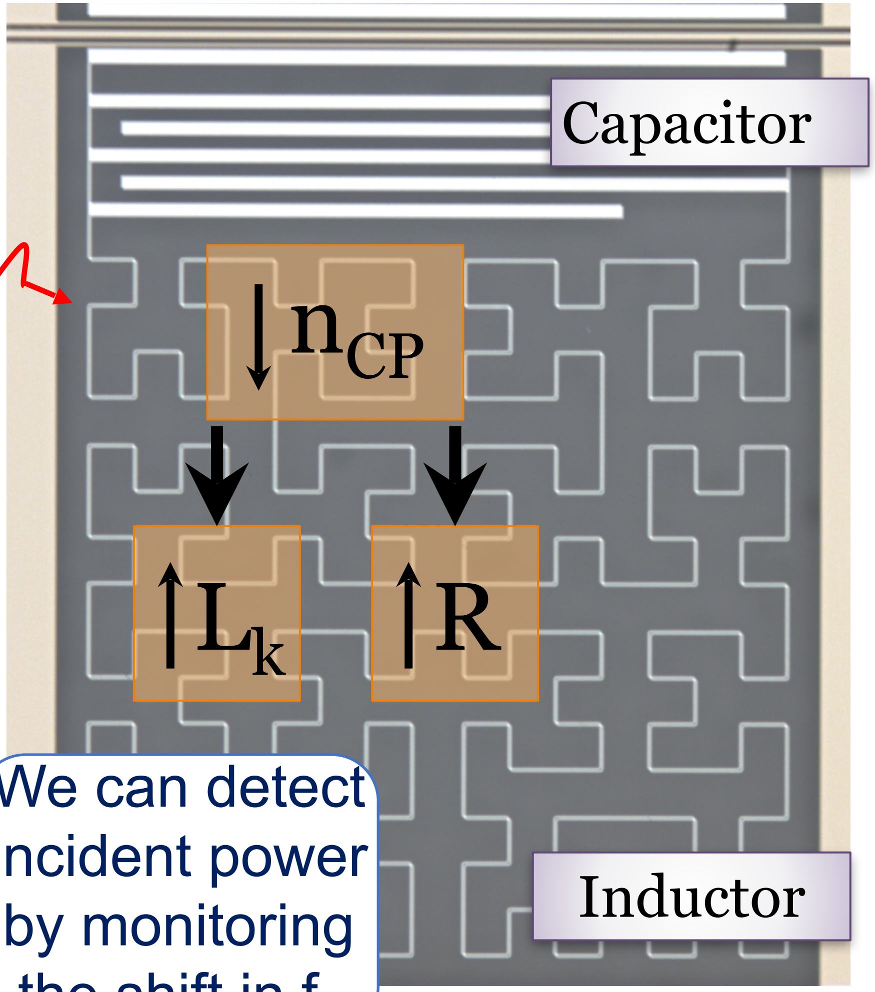
Need to test combination of **gaskets + stub**

CADEx Status: KIDs

- Detection system based on superconducting **Kinetic Inductance Detectors**



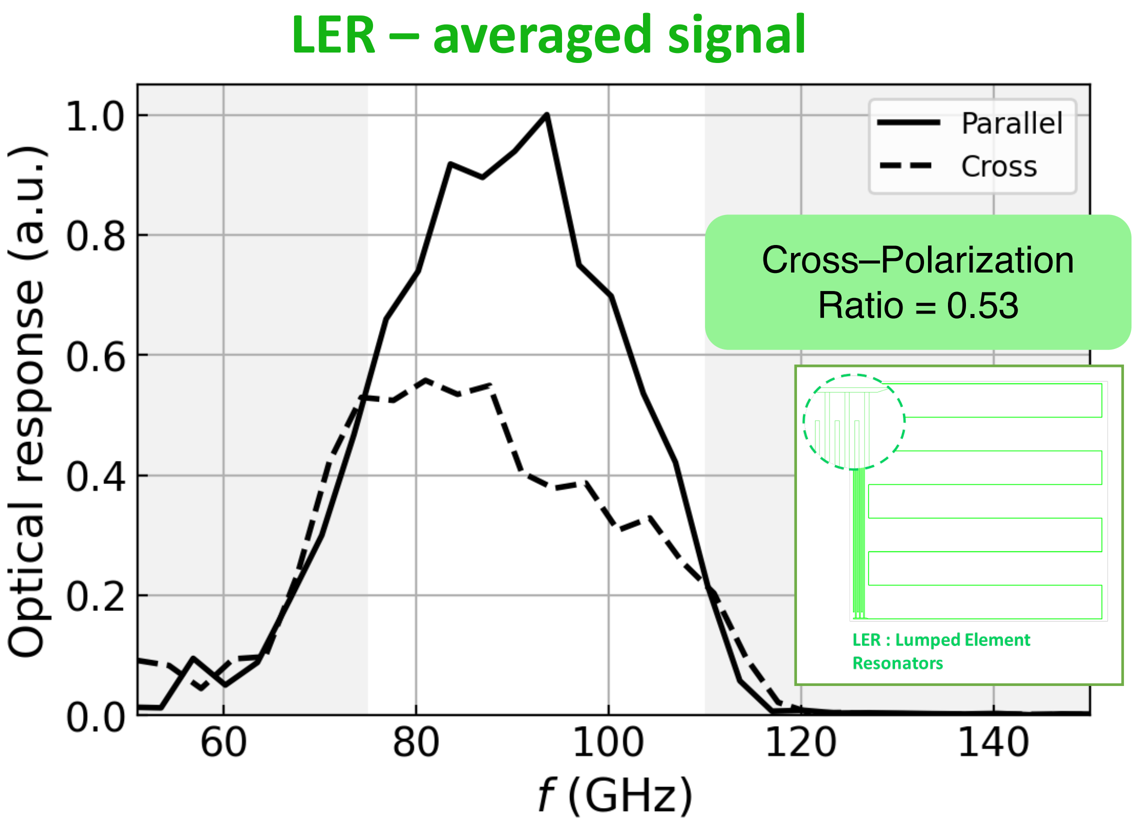


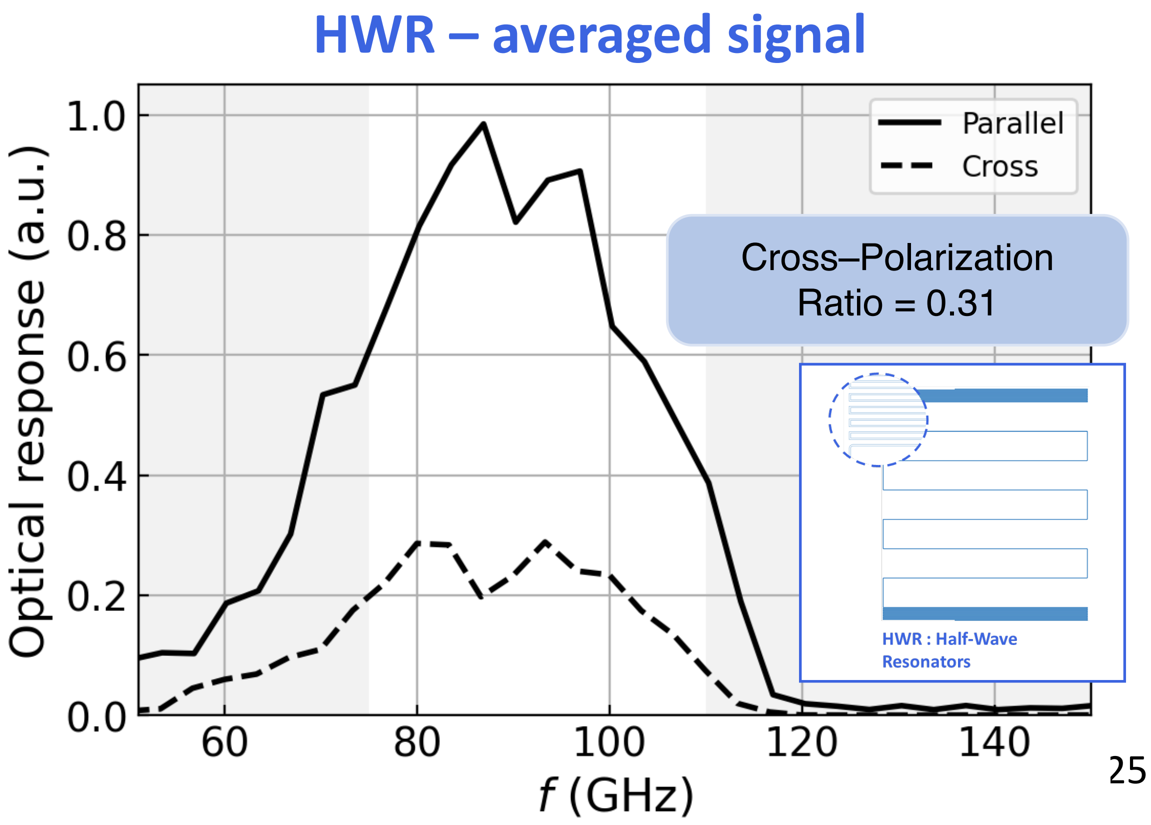


We can detect incident power by monitoring the shift in f_0

CADEx Status: KIDs

- **Broadband** detection system based on superconducting **Kinetic Inductance Detectors**
- First demonstrators based on **Ti/Al bilayer** has been developed and characterized
- Cryogenic response confirms **W-band detection**. Also reduction on **cross polarization**





KIDs Array

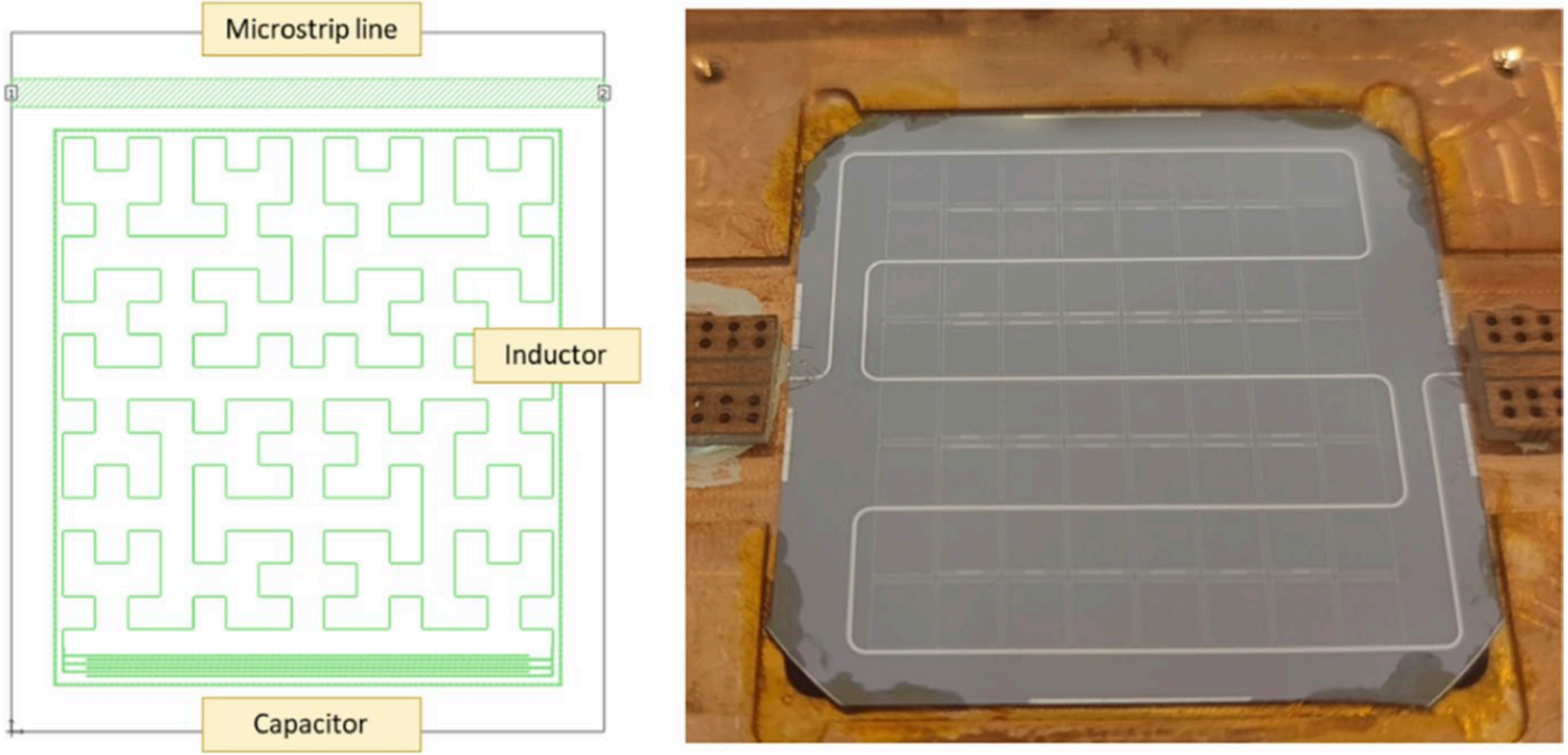


Fig. 1 *Left* schematic of a LEKID coupled to a microstrip read-out line, with the inductor and the inter-digital capacitor. *Right* photograph of the 64 LEKIDs prototype fabricated on a silicon substrate of size 40×40 mm^2

[See also Journal of Low Temperature Physics (2024)]